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Optimizing the Touch Tablet: The Effects of Lead-Lag Compensation and Tablet Size

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The display/control (D/C) gain of a touch tablet strongly affects human performance with the tablet. The primary objectives of this research were to develop and optimize a variable D/C gain that improves human performance with touch tablets. This variable gain moderates the speed-accuracy tradeoff problem associated with conventional D/C gains. An additional objective of this research was to determine the effect of tablet size on human performance.

Display/control (D/C) gain is defined as the amount of movement which occurs on the display in response to a unit amount of movement of the control. With conventional D/C gains, there is a tradeoff between low D/C gain which enables fine positioning, but results in very slow cursor movement, and high D/C gain which produces quick cursor movement but results in poor fine positioning ability. A lead-lag compensator was developed to ameliorate this tradeoff. This compensator combines a pure position gain component with a gain component proportional to the velocity of the control input.

The results indicate that the lead-lag compensator increased target acquisition rate relative to a conventional D/C gain system. Error rates were low with both systems, but were greater with lead-lag compensation than in an uncompensated system. Tablet size did not appear to affect performance.

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INTRODUCTION

As the use of computers increases, an objective of designers is the development of computer equipment that is easy and efficient to use. Several computer input devices have been developed to aid the user in entering and retrieving data. One such device is the touch tablet (also called a graphics, digitizing, or data tablet). This device translates the coordinate values of a point on the tablet into a corresponding place on the display. The tablet can be used to move a cursor, select menu items, or sketch drawings on a visual display unit. Operation of a data tablet is by finger or by stylus.

Although tablets have existed in one form or another for approximately a decade, few objective data are available to support performance comparisons between tablets and alternative input devices. Nor are there many data to guide the tablet designer so that human performance with the tablet is optimized.

There are several variables which may affect the performance of a tablet user (Arnaut and Greenstein, 1984). One of these is the display/control gain. Display/control

(D/C) gain is defined as the amount of movement which occurs on the display in response to a unit amount of movement of the control. High D/C gain enables fast cursor movement, but inhibits positioning accuracy. Low D/C gain enables accurate positioning, but slows cursor movement.

One solution to this speed-accuracy trade-off is the use of a lead-lag network compensator. Such a compensator feeds the velocity component of the control input forward to the output. This type of compensation permits enhancement of both the cursor movement and the fine positioning tasks within a single system, thereby augmenting human performance.

Lead-lag compensation of the data tablet control system was investigated as a means to improve human performance. A systematic study of several parameters which together specify the compensation network was conducted. A subsidiary research issue, the effect of touch tablet size on human performance, was also investigated. The human factors literature concerning data tablets and compensation of human-machine control systems was reviewed. The mathematical structure of the lead-lag compensation network is then formally developed. The results of an experiment which investigated the effects of lead-lag compensation and tablet size on human performance are presented and

discussed. Finally, design guidelines are developed on the basis of the experimental findings.

DATA TABLETS

Advantages

Touch tablets offer several advantages over other computer input devices. Cursor movement with tablets (and with other devices, such as the mouse or joystick) is related to natural physical tendencies. This cursor control is in contrast to keyboard commands such as "UP 6", which require users to convert the physical action into a syntactically correct command (Shneiderman, 1983).

A touch tablet provides four advantages over a touch screen device (a device in which the user points directly at the screen to input data) (Ball, Newton, and Whitfield, 1980; Whitfield, Ball, and Bird, 1983). First, a user may place both the display and the tablet wherever desired. Second, the display is not blocked by the user's hand. Third, parallax problems (due to the viewing angle of the user) do not occur. Fourth, display or touch screen device drift does not affect the input. In addition, the fatigue which lightpen or touch screen users can experience (caused by continual elevation of the hand to the screen) is unlikely to occur for touch tablet users (Ball et al., 1980; Rouse, 1975; White, 1983).

Disadvantages

Touch sensitive devices are typically slower than keyboards when used for data entry (Pfauth and Priest, 1981). Accurate positioning to within a hundredth of an inch or less, as is required for precise engineering design applications, is difficult to accomplish with a touch tablet (Foley and Wallace, 1974). Touch tablets do not allow for direct eye-hand coordination because they are somewhat removed from the display. Therefore, an indirect control-display relationship occurs which may hinder human performance (Ritchie and Turner, 1975; Swezey and Davis, 1983; Whitfield et al., 1983).

Method of Cursor Control

Arnaut and Greenstein (1984) described two ways in which the cursor may respond to a control movement of the finger or stylus, which they called absolute mode and relative mode. In absolute mode, placing a finger or stylus on the tablet causes the display cursor to move from its current position on the display to a position which corresponds to the location of the finger or stylus on the tablet. Movement of the finger or stylus results in cursor movement such that the cursor location is continually referenced to the location of the finger or stylus on the tablet. In

relative mode, placing a finger or stylus anywhere on the tablet results in no movement of the cursor. Subsequent movement of the finger or stylus (anywhere on the tablet) leads to a corresponding directional cursor movement relative to the initial cursor location.

Absolute mode gives a positional cue to the user, especially with gains close to 1.0. It also permits cursor movement to be achieved without continual contact on the tablet. There is, however, a disadvantage to absolute mode. Since the screen is mapped to the tablet, the D/C gain and screen size determine the tablet size. For a given screen size, as the gain decreases, the tablet size must increase.

An advantage of relative mode is that tablet size is independent of D/C gain. For a given D/C gain, relative mode enables the selection of a tablet size that will conform to tight space constraints. This has advantages in situations where space constraints and gain considerations together do not permit appropriate use of absolute mode.

Stylus Type

Tablets may be operated by either finger or stylus. Finger operation is convenient; people do not mislay their fingers. However, the surface area of a finger is generally larger than the surface area of a stylus, making finger

usage less precise. Operation of a tablet with a stylus allows for more precise cursor positioning; the disadvantage of the stylus is that it can be dropped or lost. Stylus types include pucks, pens, and tubes with ball-bearing tips.

Human Performance Data

Human performance data indicate that data tablets are acceptable as input and cursor positioning devices. Arnaut and Greenstein (1985) investigated gain and cursor control mode in a target selection task. D/C gains ranging from 0.61 to 2.5 were tested. Gains of 0.8 to 1.0 resulted in better performance than the higher or lower gains in terms of target selection rate (the reciprocal of the total response time per target selection) and in better performance than higher gains in terms of the number of entries into the target prior to confirmation (fewer entries into the target prior to confirmation were taken to indicate greater ease of target acquisition). In terms of response accuracy, a gain of 1.0 resulted in the smallest percentage of errors, followed in order by 1.5, 0.875, 2.0, and 2.5. Subjective ratings indicated preference for gains of 1.0 and 0.875 with respect to ease of use and fatigue.

Both absolute and relative modes of cursor control were studied. Absolute mode resulted in faster rates of

selection and fewer entries into the target area prior to confirmation. Most of the subjects (19 out of 20) preferred absolute mode. No significant difference was found between absolute and relative modes in terms of errors.

Absolute and relative modes were also studied by Ellingstad, Parng, Gehlen, Swierenga, and Auflick (1985). They conducted four studies which included text editing, tracking, and data entry tasks, and a command and control composite task consisting of single function selection, multiple function selection and data entry. They found that for the above tasks, absolute mode was superior to relative mode.

Ellingstad et al. also investigated finger versus stylus tablet operation. The stylus was a plastic tube with a plastic ball-bearing tip. Response was faster and more accurate with the stylus than with the finger.

Finally, Ellingstad et al. studied the following data insertion modes: lift-off only, lift-off plus enter (on the tablet), lift-off plus separate enter key, and separate enter key without lift-off. They found that lift-off only generally was the quickest, but also had a high error rate. The slowest response occurred with lift-off plus enter on the tablet, but this mode resulted in the fewest errors. Lift-off plus separate enter key and separate enter key

without lift-off had high response rates. The researchers concluded that lift-off only will be the preferred method of data insertion if error correction procedures (e.g., ability to re-enter incorrect data) are available. A separate off-tablet entry key is probably best if accurate data entries are critical.

Whitfield et al. (1983) compared on-display (touchscreen) and off-display (touchpad) input devices. They sought to determine how the loss of direct hand-eye coordination would affect performance. They performed three experiments, the first two with a touchscreen and a touchpad and the third with touchscreen, touchpad, and trackball. The touchscreen device was composed of a matrix of infra-red light beams across the display surface. The touchpad device was a pressure sensitive device. In all experiments, subjects selected target items from an array of items on the screen. Subjects were told to work accurately, but also as quickly as possible. The researchers recorded response time (broken down into selection time and confirmation time), error rates, and subjective comments.

The first experiment was a low resolution menu selection task. The researchers found that the touchpad was slower than the touchscreen. In particular, the touchpad resulted in a larger confirmation time, perhaps due to the

confirmation procedure with the touchpad. This confirmation action required users to reverse finger pressure to confirm entry. The confirmation procedure on the touchscreen required users to lift their fingers to indicate confirmation. Problems with fallout error occurred on both devices. (Fallout error is the error caused by the user rolling his or her fingertip in any direction when lifting the finger from the device surface.) Subjective comments showed a marked preference for the touchscreen; the touchpad was criticized for its high activation pressure and surface stickiness.

The second experiment was a medium resolution menu selection task. Prior to this experiment a software enhancement was made to correct for fallout errors with the touchpad. No protection against fallout errors was provided for the touchscreen, although fallout errors had occurred with this device in the first experiment. Again the touchpad was significantly slower than the touchscreen. However, the touchpad was superior to the touchscreen in terms of error rates, probably due to the correction for the fallout problem. Subjective ratings indicated that preferences for ease of use were divided equally between the devices.

The third experiment involved a target acquisition task with eight target resolutions. The devices used were the touchscreen, touchpad, and trackball. The touchscreen resulted in the fastest response times, while the trackball resulted in the slowest times. For all the input devices investigated, the selection time increased as the target resolution increased. The touchpad had the largest increase in selection time at high resolutions. The touchscreen had the highest error rates, while the trackball resulted in the lowest error rates. The error rates were fairly uniform for all input devices for the five lower target resolutions but increased for the touchpad and touchscreen at the three higher target resolutions. The error rate for the trackball increased only at the highest target resolution. Subjects preferred the trackball, the researchers suggest, probably because subjects were most familiar with the trackball.

In these experiments, the touchscreen had a speed advantage over the touchpad. Both devices had comparable error rates, particularly for high resolution targets. In some conditions the touchpad was superior to the touchscreen, in terms of errors, presumably due to pure aiming errors (a problem for touchscreen users because their hands block the screen). The authors suggest that touch input devices in general should not be used with high resolution targets or with highly paced tasks.

Gomez, Wolfe, Davenport, and Calder (1982) compared a tablet with a trackball in a tracking task. The task consisted of superimposing a cursor over a target. Half of the subjects were experienced in the use of the trackball tracking device; the other half were not. None of the subjects were trained in the use of the touch tablet prior to participation in the study. Subjects were instructed to place equal stress on tracking accuracy and speed of response. Use of finger or stylus was permitted, but was not systematically varied. All subjects received training in the use of both the tablet and the trackball (regardless of prior experience) before the experiment was performed. There was no significant difference in response time between devices. There was a significant difference in error magnitudes (the number of pixels away from the target), with the trackball resulting in smaller errors. Fallout problems with the tablet appeared to contribute to the error magnitude. No significant differences were found between trained and untrained subjects in mean response time. Both trained and untrained subjects had lower error magnitudes when using the trackball then when using the touch tablet. The researchers concluded that a touch tablet may be a useful input device if tracking accuracy is not an important component of the task.

Albert (1982) examined human performance in a cursor positioning task. The input devices he studied were the touchscreen, lightpen, data tablet with puck, trackball, position joystick, force joystick, and the keyboard. The task involved positioning the cursor within a target and then confirming that target. He found that the touchscreen resulted in the fastest positioning times, while the tablet resulted in a medium positioning speed (measured in pixels per second). In terms of positioning accuracy, defined as the number of pixels from target center, the tablet was the second most accurate device. The trackball was the most accurate device. Subjective ratings indicated that the tablet was the least tiring device, among the most comfortable, and the easiest to learn.

In summary, the touch tablet appears to be a useful input device with an error rate comparable to other input devices. A touch tablet may be used for tracking, data entry, and selecting targets or menu items. However, the few studies conducted thus far appear to recommend against use of the touch tablet in highly paced tasks or high tracking accuracy tasks.

CONTROL SYSTEMS

An important aspect of a person-machine system is the response of that system to control inputs. In general, the human operator is capable of controlling systems characterized by a zero or first order of control (Singleton, 1974). However, a human operator generally cannot control higher order systems easily. To perform effectively with a second-order control system, the human operator must estimate velocities, accelerations, and future position based upon current and past positions (McCormick and Sanders, 1982). A human operator is generally incapable of performing such continuous estimation tasks well. Therefore, several methods of control system compensation have been developed to make the operator's job easier.

One compensation method is termed "aiding." An aided control system modifies the response of a person-machine system so that a human operator can control the system more effectively. A rate-aided control is one in which control displacement gives the output not only a proportional displacement but an increment of velocity as well (Bekey, 1970). A block diagram of the basic rate-aided control

configuration is presented in Figure 1. The θ represents the human operator's control input. Experimental data have indicated that the optimum aiding ratio (K1/K2) should be between 0.2 and 0.8 over a range of experimental conditions (Frost, 1972).

A somewhat different sort of aiding scheme might be incorporated into the dynamics of a touch tablet to enhance human performance with this device. In continuous control tasks, high D/C gain generally permits fast movement to the general area of a target, but makes fine positioning onto the target difficult. Low D/C gain facilitates fine positioning, but increases the time needed for gross movement to the general target area (McCormick and Sanders, 1982). It might therefore be desirable to employ high D/C gain during gross movement and low D/C gain during fine positioning. Because the human's control input tends to be rapid (i.e., have high velocity) during gross movement and more gradual (lower velocity) during fine positioning, specifying the response of a control device to be a function of control input <u>velocity</u> as well as control input displacement might cause the effective D/C gain to vary automatically as desired.

A block diagram of conventional touch tablet operation is shown in Figure 2. The touch tablet is represented by the

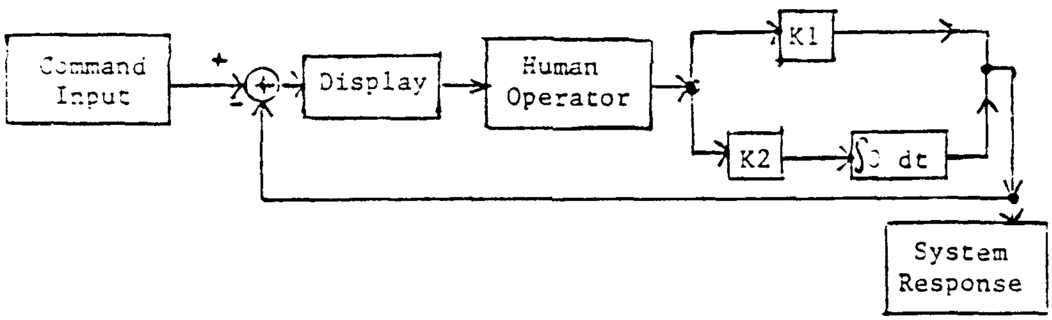


Figure 1: Rate-Aided Control System

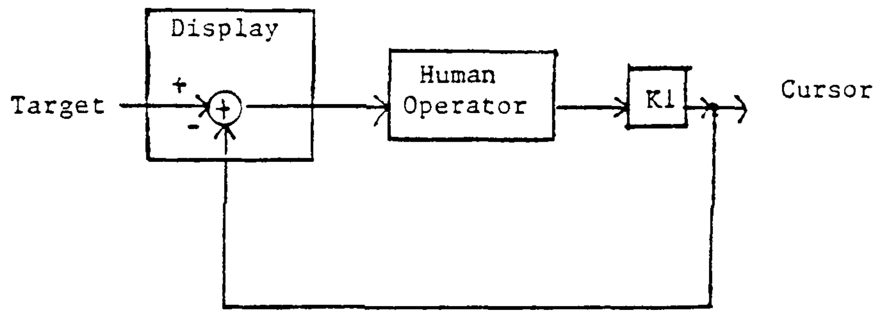


Figure 2: Conventional Touch Tablet Operation

gain constant K1. It is possible to achieve the aided system by modifying the block diagram as shown in Figure 3. In this system, displacement of the control input results in a proportional displacement of the output as in the conventional system. But the derivative of control displacement (control velocity) results in a proportional displacement of the output as well. Unfortunately this control system (termed a phase lead network, Kuo, 1982) is very susceptible to noise. Differentiating the input can result in very large and undesirable responses to inputs corrupted by noise. In order to reduce this system's susceptibility to noise, a phase lag network can be added, resulting in the system diagrammed in Figure 4.

The network diagrammed in Figure 4 is referred to as a lead-lag compensation system. A phase lead network has the advantage of fast dynamic response. However, because of its large bandwidth, the system is susceptible to noise. A phase lag network decreases system bandwidth and suppresses high frequency noise. However, such a network is also characterized by slow transient response (Dorf, 1980; Kuo, 1982). Proper selection of the lead and lag components of a lead-lag network can achieve fast dynamic response for a selected range of input frequencies coupled with suppression of very high frequency inputs that are attributable to

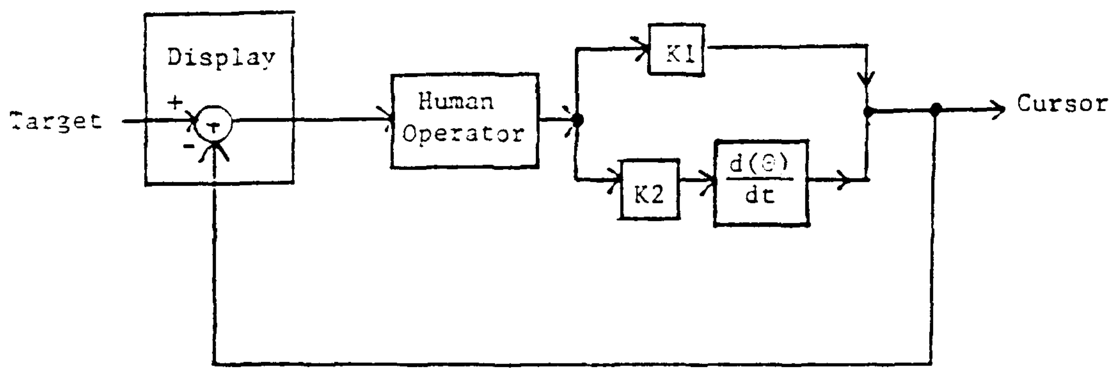


Figure 3: Modified Touch Tablet

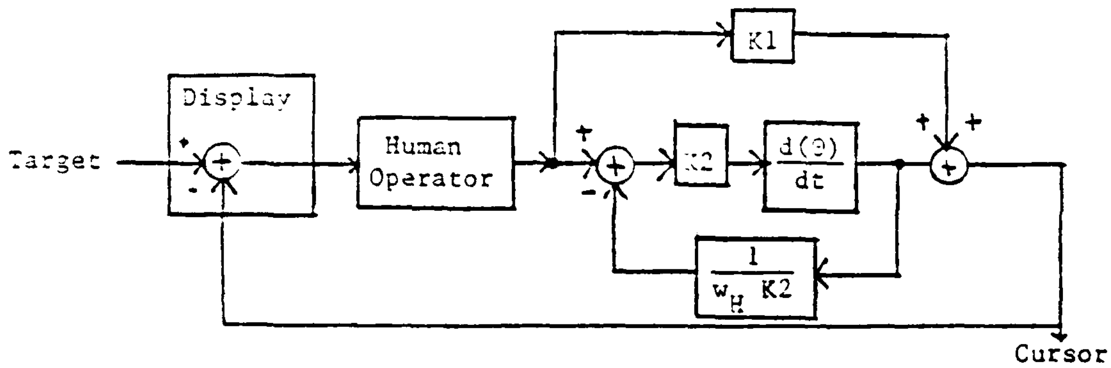


Figure 4: Lead-lag Touch Tablet Control System

noise. In the following section the mathematics and frequency response characteristics of this network will be developed formally.

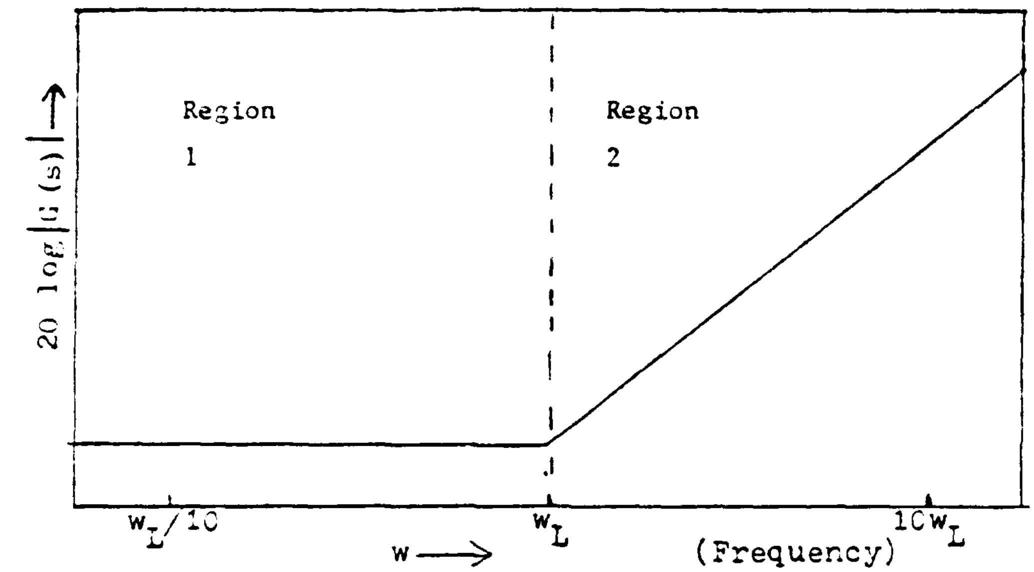
MATHEMATICAL DEVELOPMENT

The output of the touch tablet diagrammed in Figure 3 is a function of both the position and velocity of the human operator's control input. The transfer function of the compensated tablet is K1 + K2s, where s is the Laplacian operator. However, as noted in the preceding section, the controller diagrammed in Figure 3 is not practical. The response of the system to high frequency inputs causes it to be very sensitive to noise. As a result, small amounts of noise introduced through the input or by the system itself would be magnified into noticeably erratic cursor response. A pole can be added to the transfer function at some high frequency w_H to limit the sensitivity of the controller to noise. This pole places a ceiling on the response of the tablet to high velocity inputs. Such a system is diagrammed in Figure 4. The transfer function of the tablet now becomes

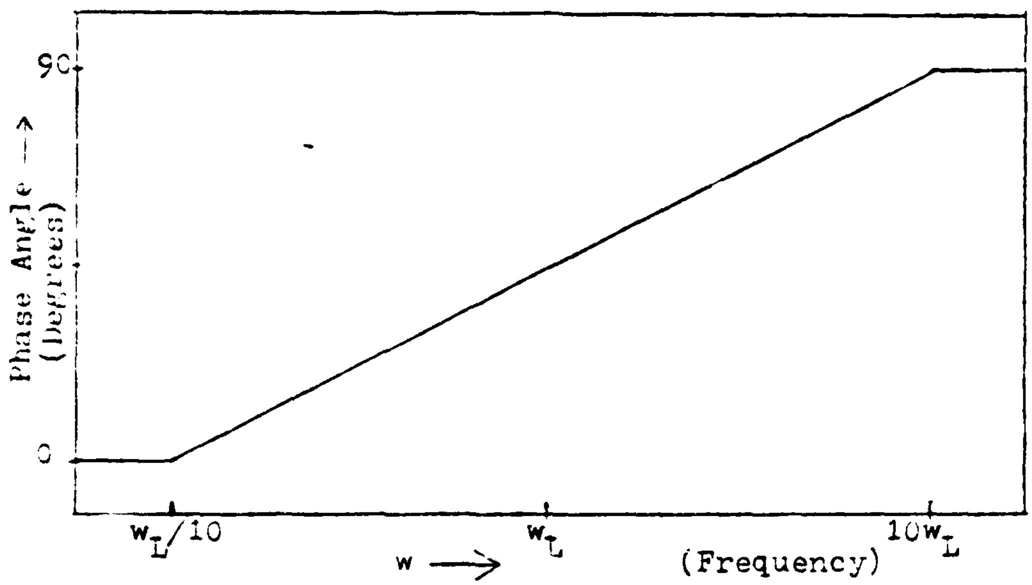
$$G(s) = K1 + K2s/[(s/w_H) + 1]. \quad (1)$$

The effect of the added pole may be seen in the Bode plots of the transfer functions. Figure 5 shows the Bode plots before the addition of a pole and Figure 6 shows the plots after the pole is added. For control inputs with velocities within region 1, the lead-lag system responds as a pure position control with gain K1. For inputs with velocities in region 2, the gain of the system increases with increasing velocity of the input as though the system were a phase lead network. For inputs with velocities in region 3, the gain of the system remains constant at some maximum value K3, reflecting the effects of the phase lag network. Note that in region 2 the slope of the magnitude plot is 20 dB per decade.

The transfer function of the lead-lag system (Equation (1)) was originally specified in terms of three parameters: the position gain, K1; the velocity gain, K2; and the location of the pole incorporated into the system to limit its susceptibility to noise, w_H. The Bode plots of the system, presented in Figure 6, describe the response of the system in terms of four parameters: K1; w_L, the 3 dB corner frequency for the onset of gain related to the velocity of the control input; w_H; and K3, the maximum total gain applied to high velocity inputs. Both w_L and K3 can be expressed in terms of the original three parameters of the transfer function, K1, K2, and w_H (see Appendix A).

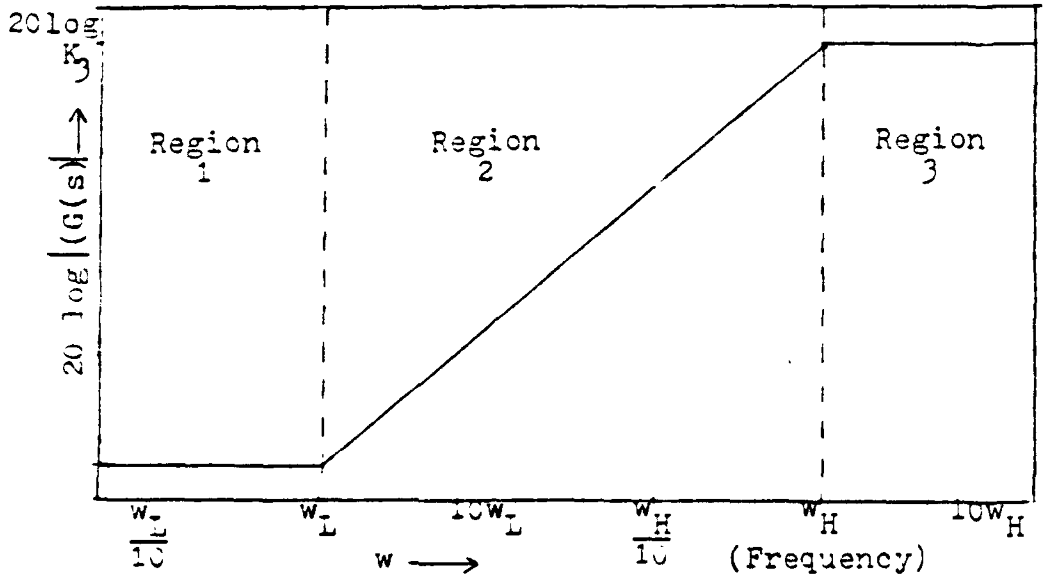


a. Bode Magnitude Plot for Transfer Function: $K_1 + K_2s$

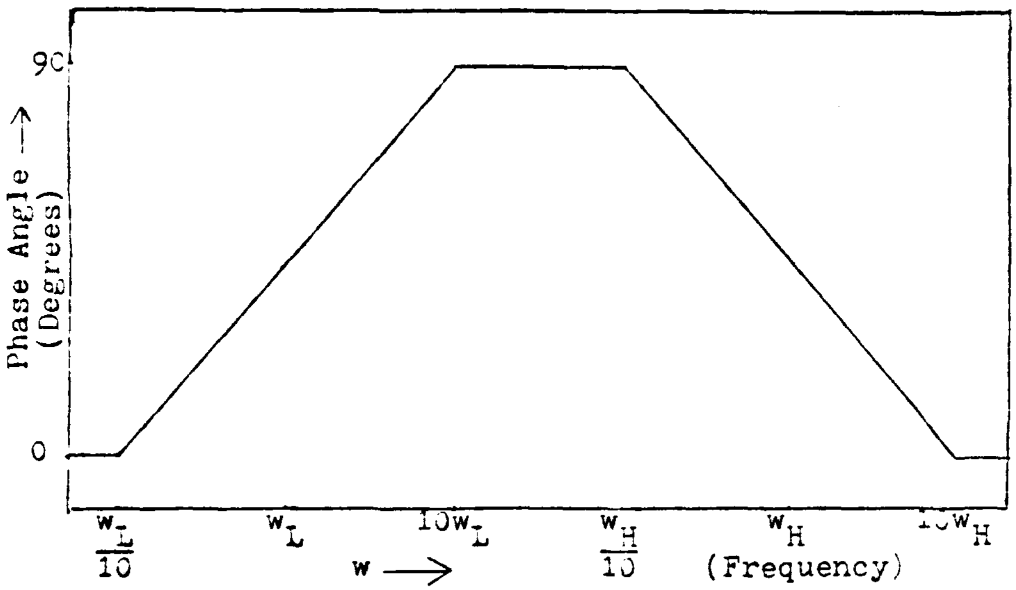


b. Bode Phase Plot for Transfer Function: $K_1 + K_2s$

Figure 5: Bode Magnitude and Phase Plots for $K_1 + K_2s$.



a. Bode Magnitude Plot for Modified Transfer Function.



b. Bode Phase Plot for Modified Transfer Function.

Figure 6: Bode Magnitude and Phase Plots for Modified Transfer Function.

The analog transfer function of the compensated control system must be transformed into a digital filter representation if the compensator is to be implemented in software on a digital computer. Breaking the transfer function into its two additive components,

$$G(s) = G_1(s) + G_2(s) = K1 + K2s/[(s/w_H) + 1]. \qquad (2)$$

$G_1(s)$ is a simple position gain K1 that is easily programmed directly. $G_2(s)$ represents the lead-lag compensator

$$G_2(s) = K2s/[(s/w_H) + 1]. \qquad (3)$$

For ease of exposition Equation (3) will be rewritten as

$$G_2(s) = K2s/[T_H s + 1], \qquad (4)$$

where T_H is simply the reciprocal of w_H. The next step is to transform Equation (4) into a digital filter using the bilinear transform method (Oppenheim and Schafer, 1975, pp. 206-211). The expression below is substituted for s in (4).

$$s = \frac{2\ (1 - z^{-1})}{T\ (1 + z^{-1})}. \qquad (5)$$

T is the sampling period of the digital system and z^{-1} is the delay operator. This yields

$$G_2(z) = \frac{2K2 - 2K2z^{-1}}{(2T_H + T) + (T - 2T_H)z^{-1}} . \qquad (6)$$

Efficient methods of implementing digital filters exist (Oppenheim and Schafer, 1975). The method used here requires that the transfer function of the digital filter be of the form

$$G_2(z) = \frac{\sum_{k=0}^{M} b_k z^{-k}}{1 - \sum_{k=1}^{N} a_k z^{-k}} . \qquad (7)$$

Equation (6) is therefore rearranged to the appropriate form

$$G_2(z) = \frac{\dfrac{2K2 - 2K2z^{-1}}{2T_H + T}}{1 + \dfrac{(T - 2T_H)z^{-1}}{T + 2T_H}} \qquad (8)$$

and can thus be expressed as

$$G_2(z) = (b_0 + b_1 z^{-1})/(1 - a_1 z^{-1}), \tag{9}$$

where:

$$b_0 = 2K2/(2T_H + T),$$

$$b_1 = -2K2/(2T_H + T),$$

and

$$a_1 = (2T_H - T)/(2T_H + T). \tag{10}$$

The digital filter may then be implemented with the block diagram illustrated in Figure 7 (Oppenheim and Schafer, 1975, pp. 148-151). The equations described by the block diagram are

$$q_n = w_{n-1}, \tag{11}$$

$$w_n = x_n + a_1 q_n, \quad \text{and} \tag{12}$$

$$y_n = b_0 w_n + b_1 q_n, \tag{13}$$

where x_n is the input position from the touch tablet, w_n is an intermediate value, q_n is the previous intermediate value, and y_n is that component of the system response attributable to the velocity of the input. The variable q_0 is initialized to zero. The velocity response component, y_n is added to the position response component, $K1x_n$. Note that there are two channels, one for the horizontal direction and one for the vertical direction.

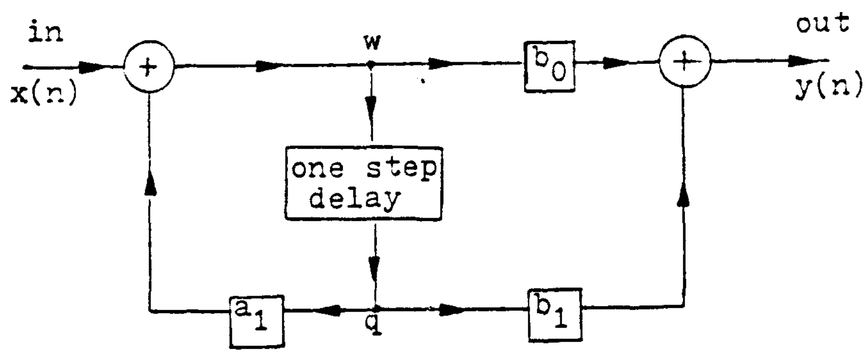


Figure 7: Digital Filter Block Diagram.

RESEARCH OBJECTIVES

Unlike most of the past research which has compared touch tablets to other computer input devices, this report is committed to the development of touch tablet design. The primary objective of this report is to study the effect of a lead-lag controller on human performance with a touch tablet. This research approaches the design of touch tablets in a unique manner. A search of the open literature reveals no research conducted on touch tablets which involved the use of a lead-lag controller.

A lead-lag controller is specified by three parameters, such as the position gain, K1; the velocity gain, K2; and the limiting gain at the high frequency cutoff, K_3. The variables K1, K2, target size, and tablet size are considered in this research effort. The value of K3 was determined based on pretest data and was set to a constant value throughout the experiment.

The relative method of cursor control was used exclusively for two reasons. First, with the addition of a gain dependent on control input velocity, only a limited form of absolute cursor control (in which the initial

location of the display cursor is tied to the location of the initial touchdown upon the tablet) could be implemented as an alternative to relative mode. Once the velocity gain takes effect, the one-to-one mapping of tablet location to display cursor location characteristic of absolute mode is necessarily lost. Second, as mentioned in the discussion of touch tablets earlier in this report, relative mode permits tablet size to be selected independently of D/C gain, thus permitting the system designer additional flexibility in highly constrained workspace situations.

The objective of this report is to gain knowledge regarding the effect of a lead-lag controller on touch tablet operation. A subsidiary research issue concerns the effect of tablet size and its interaction with lead-lag compensation on human performance.

EXPERIMENTAL METHOD AND DESIGN

Apparatus and Display

The task was presented on an IBM 5153 Model 1 31.75-cm color display. A 27.94- x 27.94-cm Elographics E-233 pressure sensitive tablet was placed on the table in front of the display. An overlay was placed on the tablet to indicate the active and confirmation (lower right corner) areas of the tablet as depicted in Figure 8. Subjects used a stylus on the tablet to effect cursor movement on the display. The stylus was a 13-cm metal tube with a plastic tip.

The display illustrated in Figure 9 was 14.63 cm x 17.07 cm. On the left and right sides of the display was a grid containing menus of function names enclosed within rectangles of small (0.51 cm^2), medium (2.04 cm^2), and large (4.63 cm^2) sizes. In the center of the display were randomly selected targets of the same small, medium, and large sizes. The targets and menu area were outlined in white on a black background.

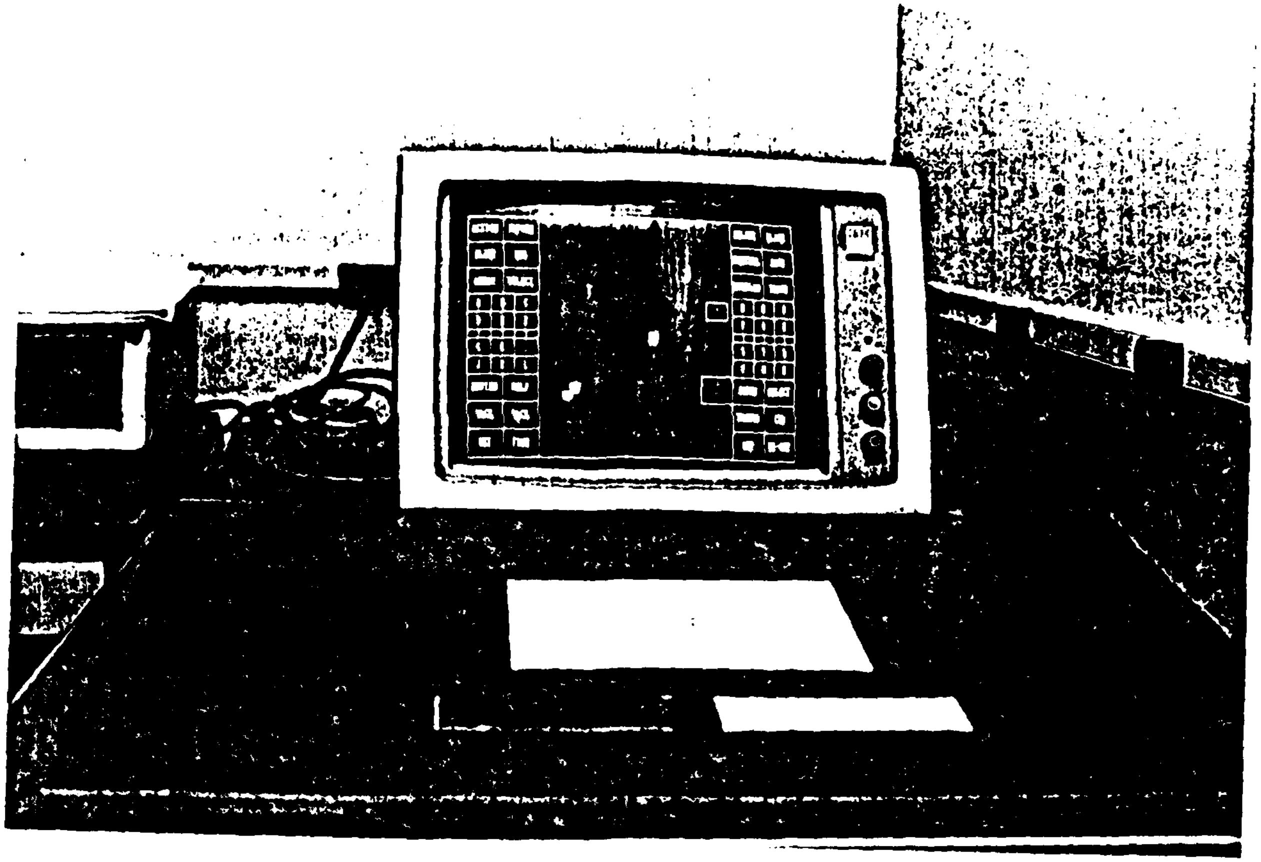


Figure 8: Tablet Layout

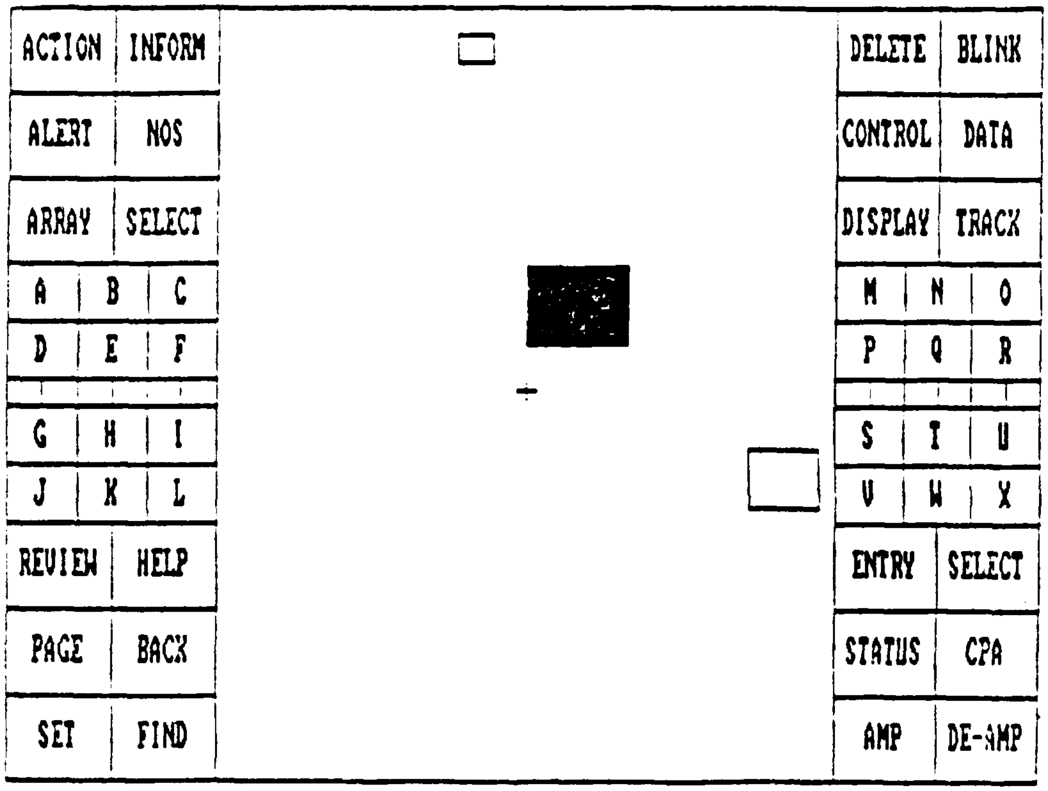


Figure 9: Screen Display.

Subjects

Six male and six female college students participated as subjects. The subjects were screened for corrected 20/22 near point visual acuity using a Bausch and Lomb Ortho-rater. Participants received $21.00 for the time spent in the experiment (5-6 hours).

Task Description

The task in this experiment was a menu selection/target acquisition task. Each trial started with a highlighted menu function or a highlighted target. The subject moved the cursor to this menu function or target and then confirmed his or her selection by lifting the stylus and touching the confirmation area with the opposite hand. A high frequency tone sounded if the selection was correct while a low frequency tone indicated an incorrect selection. A selection was considered correct if the center of the cursor was inside the target. Two seconds after confirmation, a new display was presented and two short beeps sounded to indicate the start of a new trial.

Experimental Design

The candidate independent variables in this experiment were K1, the position gain; K2, the velocity gain; K3, the limiting gain at the high frequency cutoff; target size; and tablet size. A pretest was conducted using three subjects to determine if the value of the limiting gain at the high frequency cutoff had a significant effect on performance. The results of the pretest were used to determine a value for the gain limit to be used throughout the primary study, as well as the ranges of values for the position gain and the velocity gain to be investigated in that study.

A completely within-subject experimental design was used. For the pretest, the independent variables were position gain, velocity gain, gain limit, and target size. Three levels of position gain (0.25, 0.625, and 1.0), four levels of velocity gain (0.05, 0.15, 0.25, and 0.35), three levels of gain limit (2.0, 4.0, and 6.0), and three levels of target size (small, medium, and large) were tested. Tablet size was held constant at 15.24 cm x 19.05 cm. For each position gain/velocity gain/gain limit combination the subject was required to select 30 targets, 10 each of the small, medium, and large sizes.

The results of the pretest indicated that although there was no main effect of gain limit, the interaction of

velocity gain with gain limit was significant for target acquisition rate (p = 0.0924) and number of entries into the target prior to confirmation (p = 0.0717). (Because of the exploratory nature of the pretest and the low number of subjects employed, a significance level of 0.10 was used.) These interactions are illustrated in Figures 10 and 11. Acquisition rate decreased as velocity gain increased for the low gain limit. For the medium gain limit, acquisition rate increased as velocity gain increased from 0.05 to 0.25. For the high gain limit, acquisition rate decreased as velocity gain increased from 0.15 to 0.35. The increase in number of target entries prior to confirmation, observed for all gain limits as velocity gain increased, was much greater for the low gain limit then for the medium or high gain limits as velocity gain increased from 0.25 to 0.35. Finally, the intermediate gain limit of 4.0 was preferred by two of the three subjects. On the basis of this pretest data, a gain limit of 4.0 was chosen for the primary experiment.

The main effect of position gain was significant for number of target entries prior to confirmation (p = 0.0272). As the value of position gain increased, so did the number of entries into the target. The main effect of velocity gain was significant for all dependent measures: target

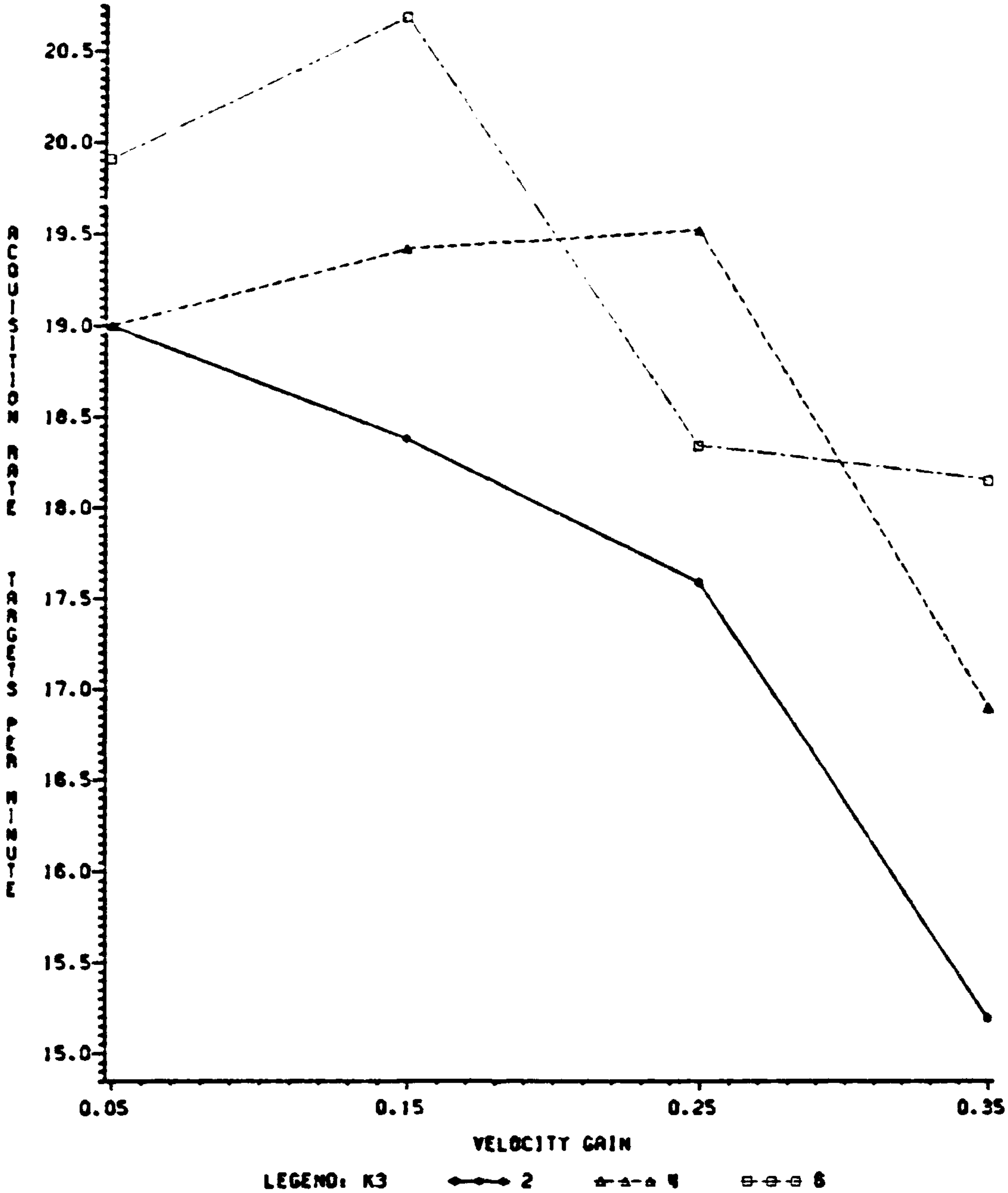


Figure 10: K2 x K3 interaction for acquisition rate.

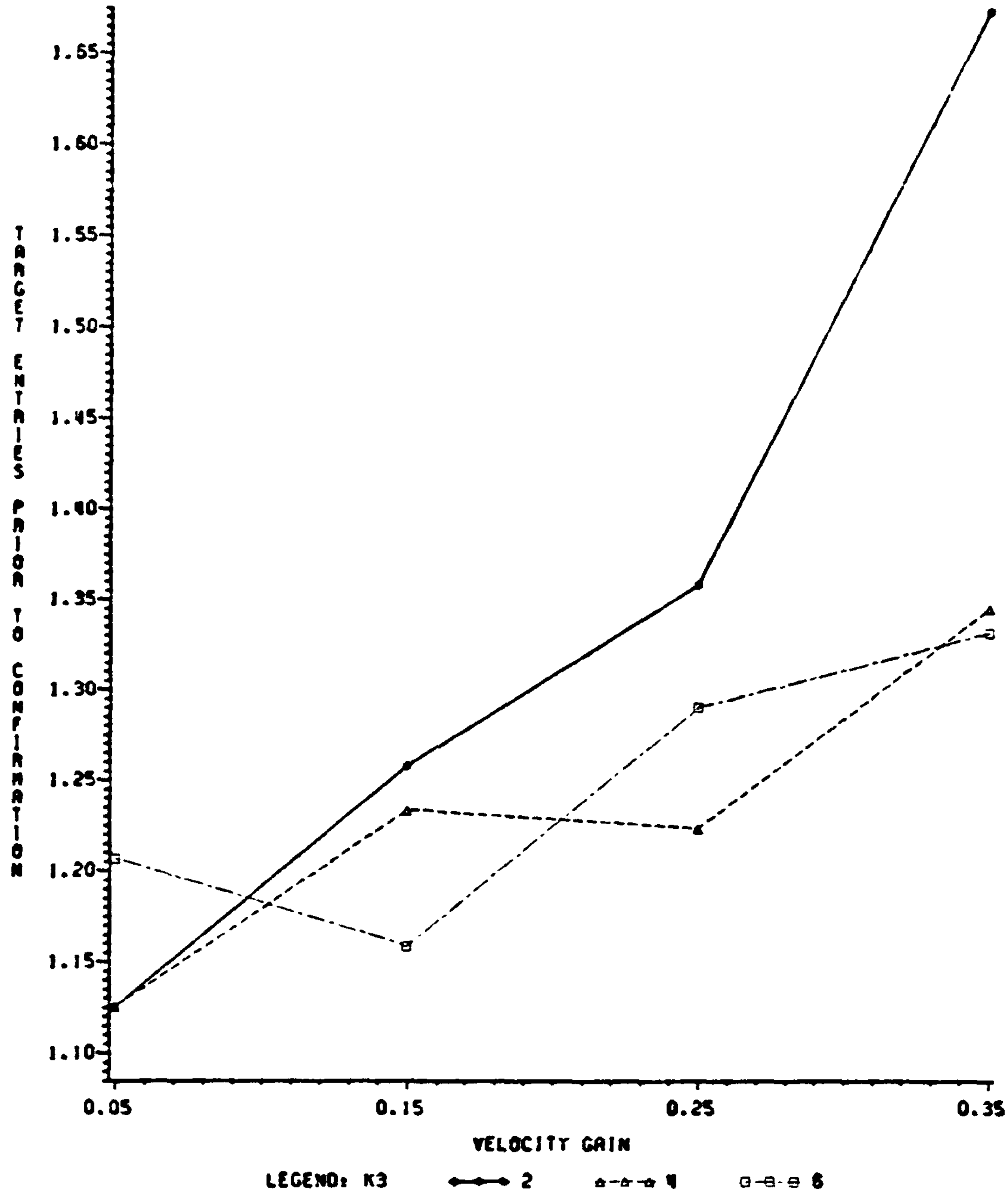


Figure 11: K2 x K3 interaction for target entries.

acquisition rate ($p = 0.0012$), number of target entries prior to confirmation ($p = 0.0074$) and error rate ($p = 0.0734$). The velocity gains of 0.05 and 0.15 resulted in faster acquisition rates, fewer target entries, and fewer errors than did the higher velocity gains.

The pretest indicated that low position gain with a low to medium additive velocity gain resulted in faster target acquisition, fewer target entries prior to confirmation, and was preferred by subjects. Since low position gain resulted in fewer target entries prior to confirmation, this value was selected for the primary study. The range for the position gain was narrowed and the position gain values of 0.25, 0.5 and 0.75 were chosen for the primary study. Since the velocity gain of 0.35 resulted in poor user performance, the largest value chosen for the primary experiment was 0.3. A velocity gain of 0.0 was included so that a pure position gain case could be compared against position gain/non-zero velocity gain combinations. Velocity gains of 0.0, 0.1, 0.2, and 0.3 were chosen for the primary experiment.

The independent variables of the primary experiment are then the position gain, K1; the velocity gain, K2; target size; and tablet size. Three position gain levels (0.25, 0.50, and 0.75), four velocity gain levels (0.0, 0.1, 0.2, and 0.3), three tablet sizes (10.16 cm x 12.7 cm, 15.24 cm x

19.05 cm, and 20.32 cm x 25.4 cm), and three target sizes (4.63 cm^2, 2.04 cm^2, and 0.51 cm^2) were tested using a completely within-subject design. The small tablet size is approximately the size of a numeric keypad, while the large size is approximately the size of the screen display.

Based on random assignment, one-third of the subjects used the large tablet size on the first day, one-third used the medium tablet size, and one-third used the small tablet size. Assignments of tablet size for the second and third days were determined using a Latin square. For each tablet size, the order of presentation of the twelve position gain-velocity gain combinations was randomized. Target size order of presentation was randomized within each treatment condition.

Procedures

Each subject was tested over three days using a different tablet size each day. On the first day, subjects signed an informed consent, read the instructions (Appendix B), and completed a practice session in which they were exposed to various D/C gain combinations (Appendix C). Each day, subjects were tested on the three values of K1 and the four values of K2. For each condition, the subject attempted to acquire 30 targets: 10 small, 10 medium, and 10 large.

Before each trial block, the subject completed 15 training trials to become familiar with the condition. The subject then performed the 30 target selections. Next, during a rest break, the subjects completed a short questionnaire (Appendix D) expressing opinions regarding the mental and physical fatigue associated with the treatment condition. At the end of the study, subjects completed a final questionnaire (Appendix E) to ascertain preferred tablet size.

RESULTS

Three dependent measures were employed: the rate of target acquisition, the number of target entries prior to confirmation, and the percentage error of target acquisition. Acquisition rate is the reciprocal of the total response time per target acquisition. A higher acquisition rate indicated more rapid task performance. The more entries into the target prior to confirmation, the more difficult the fine positioning task was considered to be. The percentage error was the percentage of responses resulting in an incorrect target acquisition. These three measures will be discussed separately.

Acquisition Rate

Table 1 contains the summary table for an analysis of variance (ANOVA) for target acquisition rate. The ANOVA indicates that there is a significant main effect of position gain. A Newman-Keuls test shows that position gains of 0.50 and 0.75 are not significantly different from each other, but are significantly different from a position gain of 0.25 ($p < 0.05$). The higher position gains result in faster target acquisition rates (Figure 12).

TABLE 1

Analysis of Variance Summary Table for Target Acquisition Rate

Source	df	MS	F	p
Between-Subject				
Subjects (S)	11	277.7		
Within-Subjects				
K1	2	236.6	35.16	0.0001
K1 x S	22	6.7		
K2	3	1173.4	104.74	0.0001
K2 x S	33	11.4		
TABLET SIZE (TS)	2	28.2	0.32	0.7304
TS x S	22	90.8		
TARGET SIZE (TGT)	2	4489.2	488.93	0.0001
TGT x S	22	13.3		
K1 x K2	6	288.9	50.91	0.0001
K1 x K2 x S	66	5.7		
K1 x TS	4	29.2	3.45	0.0154
K1 x TS x S	44	8.5		
K1 x TGT	4	10.6	2.89	0.0327
K1 x TGT x S	44	3.7		
K2 x TS	6	6.6	1.03	0.4161
K2 x TS x S	66	6.4		
K2 x TGT	6	162.8	48.13	0.0001
K2 x TGT x S	66	3.4		
TS x TGT	4	0.9	0.19	0.9412
TS x TGT x S	44	4.5		

TABLE 1, Continued

K1 x K2 x TS	12	7.3	1.06	0.4006
K1 x K2 x TS x S	132	6.9		
K1 x K2 x TGT	12	9.2	2.44	0.0067
K1 x K2 x TGT x S	132	3.8		
K1 x TS x TGT	8	7.1	2.71	0.0103
K1 x TS x TGT x S	88	2.6		
K2 x TS x TGT	12	6.1	1.76	0.0609
K2 x TS x TGT x S	132	3.4		
K1 x K2 x TS x TGT	24	2.5	0.83	0.7032
K1 x K2 x TS x TGT x S	264	3.1		
Total	1295			

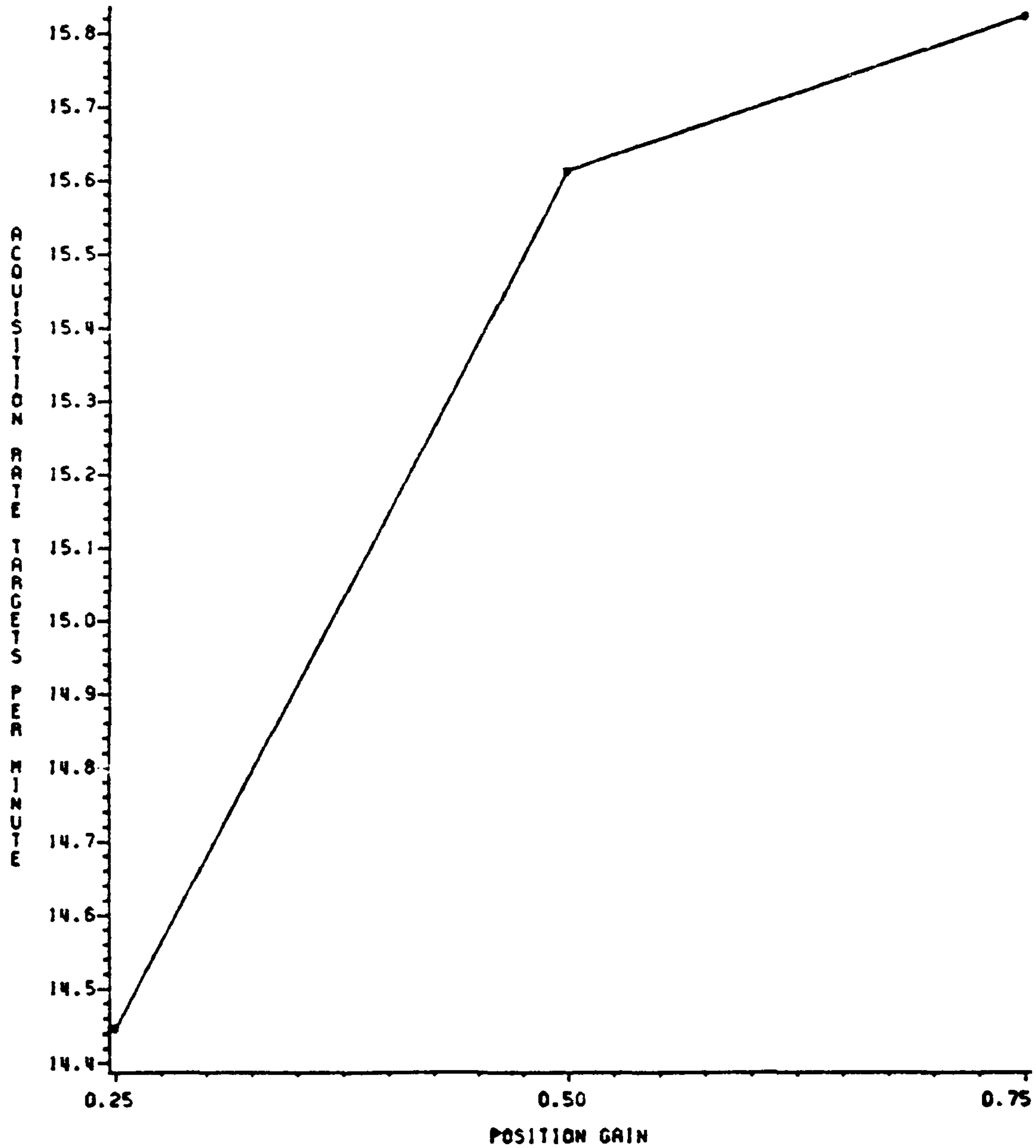


Figure 12: Position gain main effect for target acquisition rate.

There is a significant main effect of velocity gain. A Newman-Keuls test shows significant differences among all four velocity gains ($p < 0.05$). Maximum target acquisition rate occurs at the 0.1 velocity gain (Figure 13). Acquisition rate decreases as velocity gain increases from this value. However, every non-zero velocity gain achieves faster acquisition rates than the zero velocity gain.

The main effect of target size is significant. A Newman-Keuls test showed significant differences among all three levels of target size ($p < 0.05$) (Figure 14). Large targets are acquired more quickly than medium targets and medium targets are acquired more quickly than small targets. Thus, it is easier to position the cursor inside a large target area than inside a small target area.

The main effect of tablet size was not significant.

A significant interaction of position gain with velocity gain indicates that increases in the value of the position gain significantly increase target acquisition rate for the uncompensated system, but have little effect for systems in which the velocity gain is non-zero. A Newman-Keuls test (Table 2) shows that velocity gains of 0.2, combined with low or medium position gain, and of 0.1 with any position gain yield the highest target acquisition rates (Figure 15).

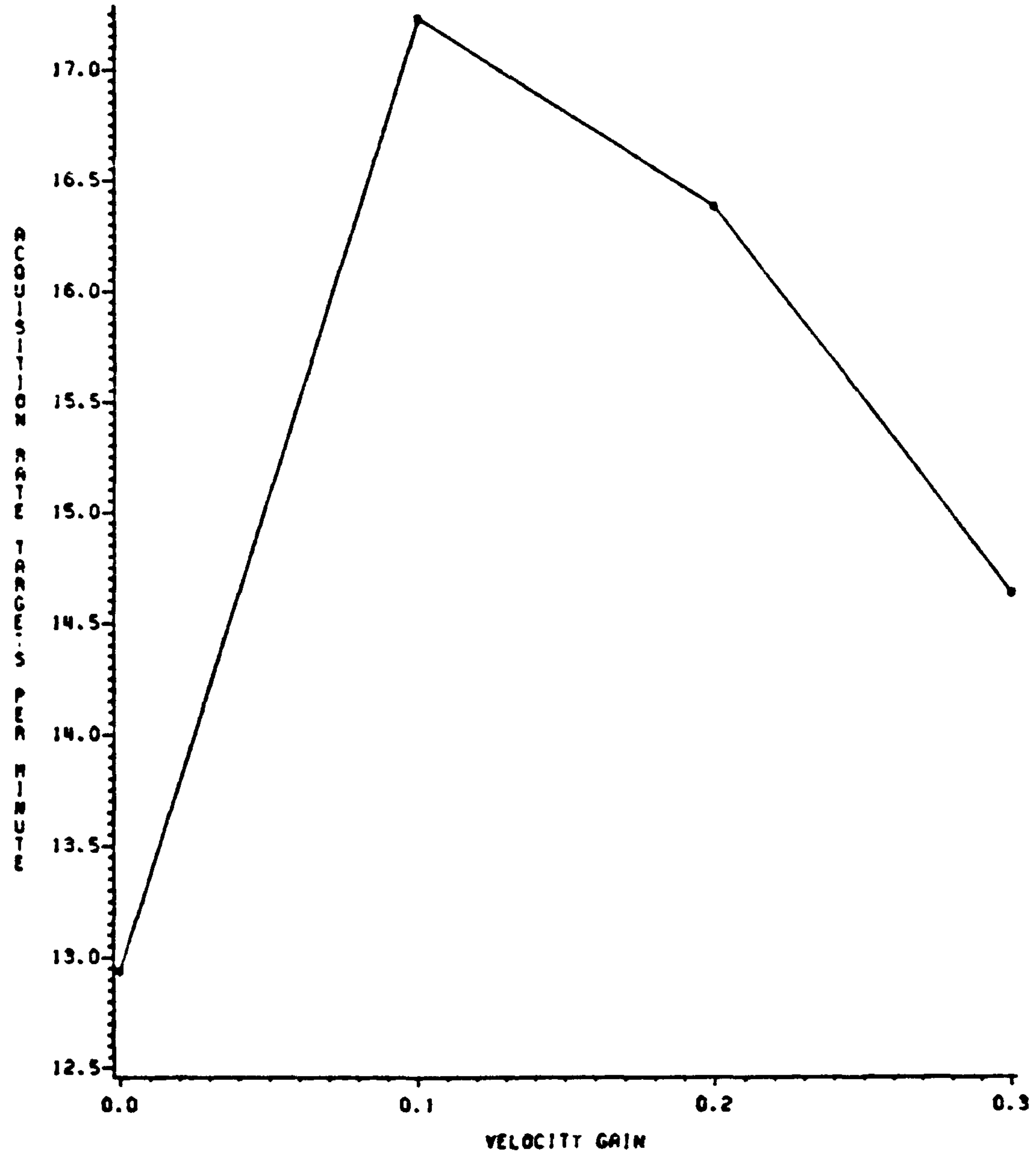


Figure 13: Velocity gain main effect for target acquisition rate.

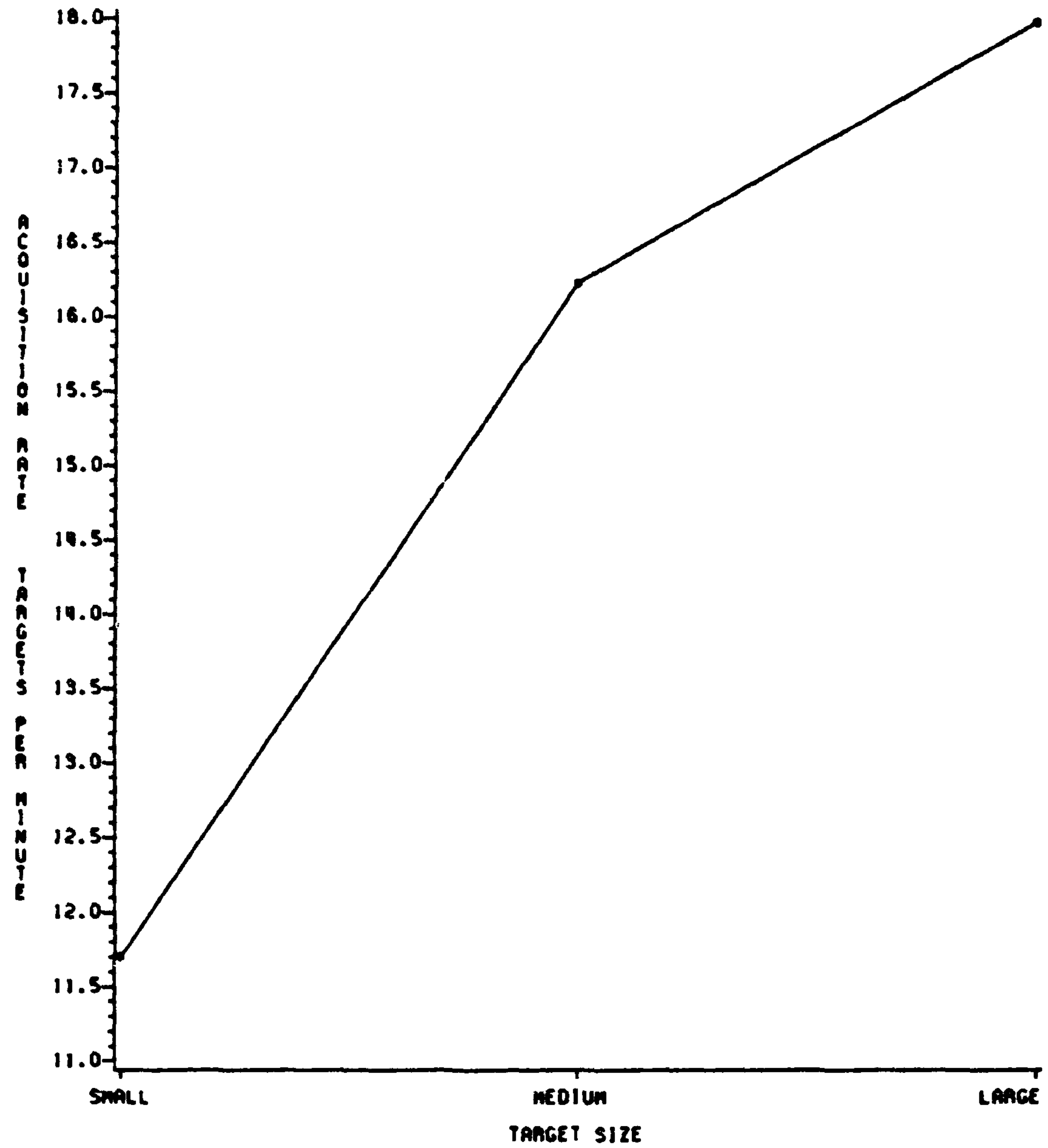


Figure 14: Target size main effect for target acquisition rate.

TABLE 2

Newman-Keuls Test Results for K1 x K2 Interaction for Acquisition Rate

K2	K1	Mean Rate						
0.0	0.25	9.46	A					
0.0	0.50	13.71		B				
0.3	0.75	14.27		B	C			
0.3	0.25	14.77			C			
0.3	0.50	14.87			C	D		
0.0	0.75	15.64				D		
0.2	0.75	16.04				D	E	
0.2	0.25	16.46					E	F
0.2	0.50	16.62					E	F
0.1	0.25	17.10						F
0.1	0.50	17.24						F
0.1	0.75	17.32						F

Alpha level = 0.05.

Means with the same letter are not significantly different.

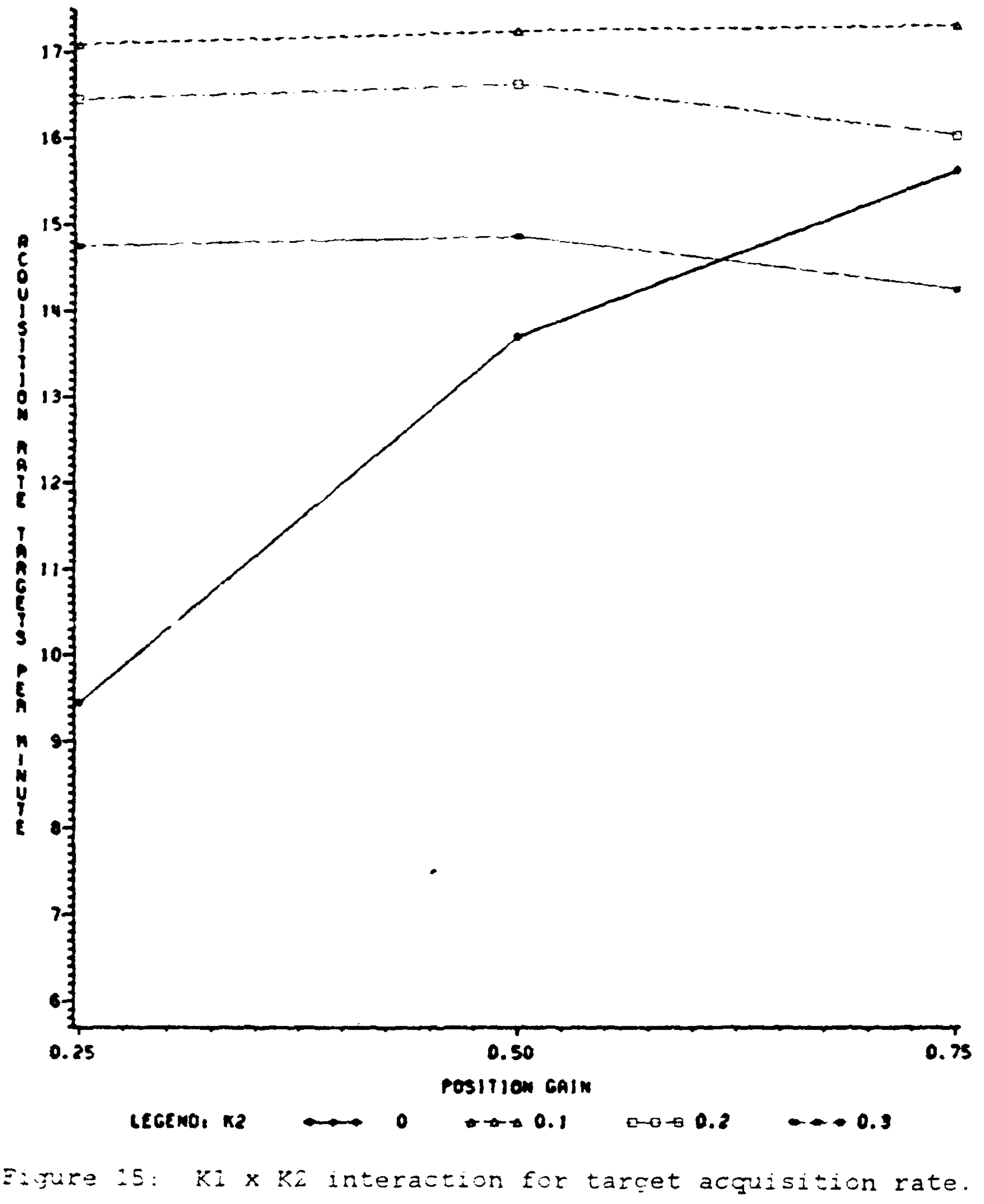


Figure 15: K1 x K2 interaction for target acquisition rate.

The interaction of position gain (K1) with tablet size (TS) is significant. A Newman-Keuls test (Table 3) shows that the combinations of medium or high position gain with any tablet size achieve the highest target acquisition rates (Figure 16). The significant interaction suggests that, in terms of target acquisition rate, a small tablet with low position gain yields performance that can be significantly improved by increases in tablet size or position gain.

The significant interaction of position gain (K1) with target size (TGT) appears to indicate that high position gain has a different effect on the acquisition of smaller targets than for larger targets. Performance increased with each increase in position gain for large targets, but leveled off above the medium position gain for small and medium targets. Table 4 presents the results of the Newman-Keuls test, while Figure 17 illustrates the interaction. This result suggests that fine positioning becomes difficult with small target areas at high position gains.

For each level of target size, the highest acquisition rate is achieved with velocity gain of 0.1 (Figure 18). In all cases except the velocity gain of 0.3/small target size case, a non-zero velocity gain aids performance relative to zero velocity gain. The results suggest that increases of

TABLE 3

Newman-Keuls Test Results for K1 x TS Interaction for Acquisition Rate

K1	TS	Mean Rate	
0.25	small	13.84	A
0.25	med.	14.64	B
0.25	large	14.85	B
0.50	med.	15.12	B C
0.75	small	15.40	B C
0.50	large	15.85	C
0.50	small	15.86	C
0.75	large	15.95	C
0.75	med.	16.12	C

Alpha level = 0.05.

Means with the same letter are not significantly different.

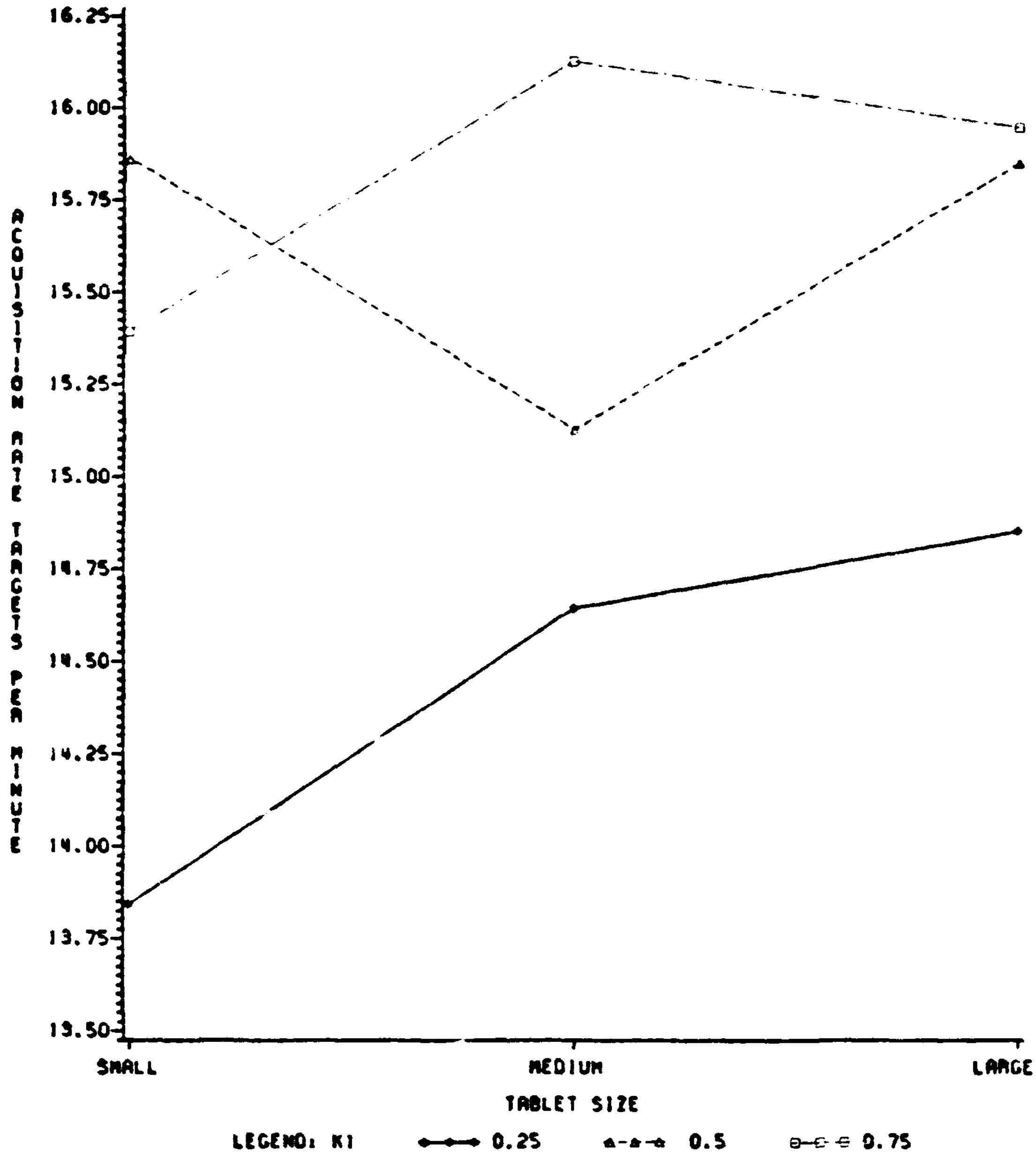


Figure 16: K1 x TS interaction for target acquisition rate.

TABLE 4

Newman-Keuls Test Results for K1 x TGT Interaction for Acquisition Rate

TGT	K1	Mean Rate	
high	0.25	11.07	A
	0.50	12.16	B
	0.75	11.89	B
med.	0.25	15.34	C
	0.50	16.47	D
	0.75	16.85	D
low	0.25	16.93	D
	0.50	18.21	E
	0.75	18.72	F

Alpha level = 0.05.

Means with the same letter are not significantly different.

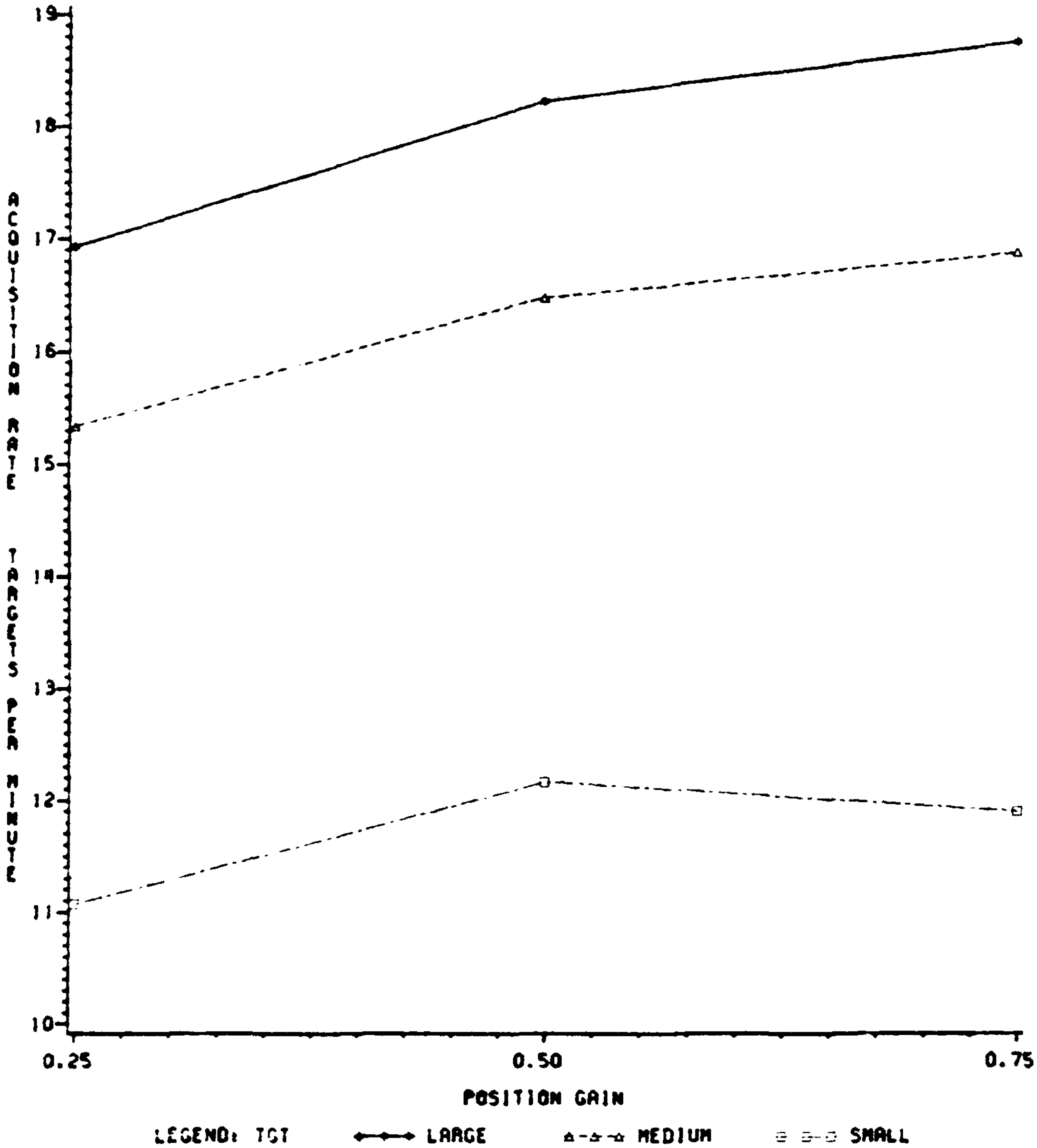


Figure 17: K1 x TGT interaction for target acquisition rate.

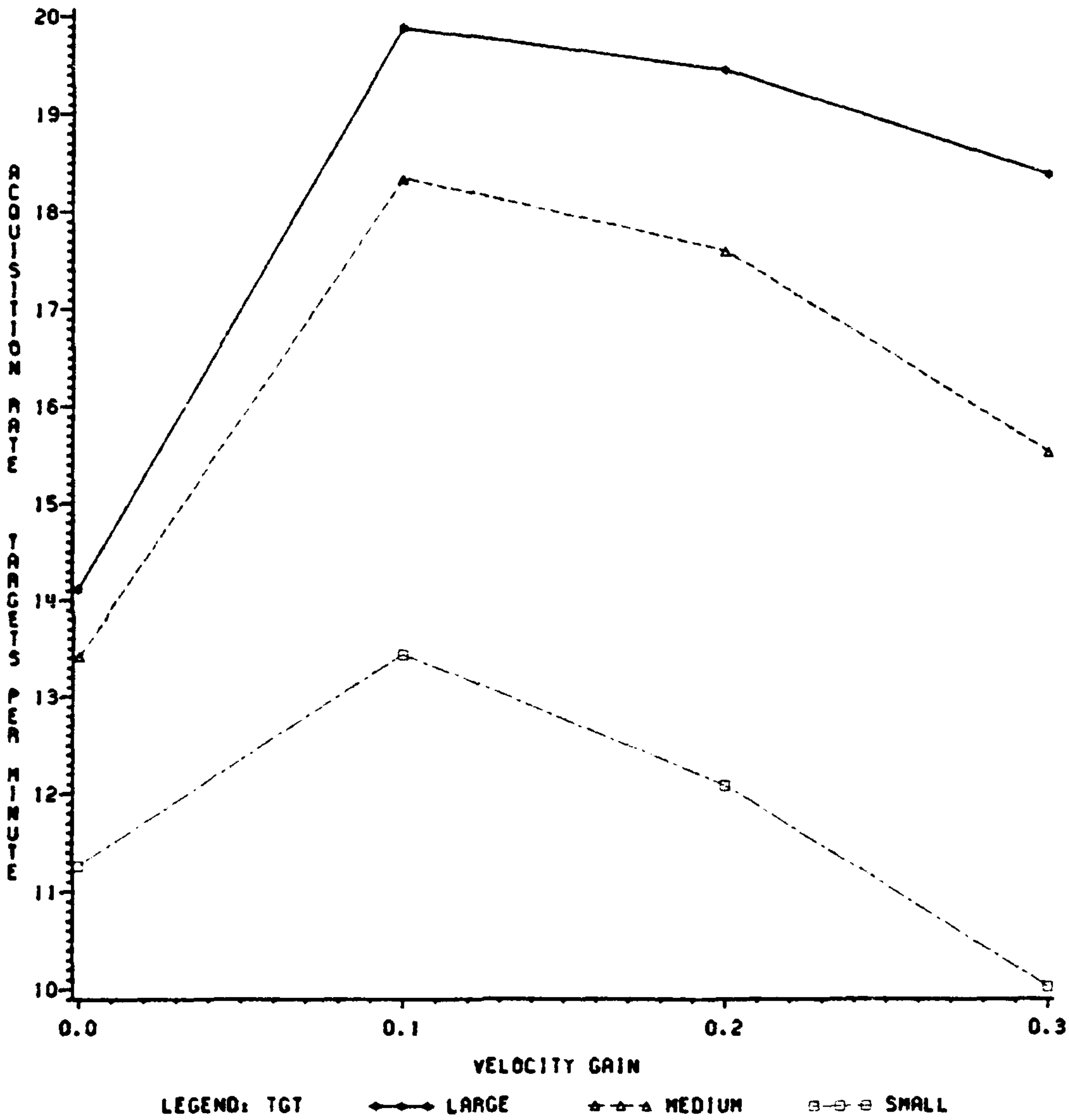


Figure 18: K2 x TGT interaction for target acquisition rate.

the velocity gain from 0.0 to 0.1 achieve larger increases in acquisition rates for medium and large targets than for small targets. It also appears that increases of velocity gain from 0.1 to 0.3 cause larger decreases in acquisition rates for small and medium targets then for large targets. Thus, velocity gain hinders acquisition of smaller targets more than the acquisition of larger targets. Table 5 contains the Newman-Keuls test results.

The K1 x K2 x TGT interaction is significant (Figure 19). A simple-effects F test on the K1 x TGT combinations (Table 6) indicates that the main effect of target size is significant for each velocity gain. A Newman-Keuls test shows that all three target sizes are significantly different from each other for each velocity gain. Target acquisition rate increases as target size increases for all velocity gains.

The main effect of K1 is significant for only the zero velocity gain. Target acquisition rate increases with increasing position gain. This effect is not significant for non-zero velocity gains, indicating that when velocity gain is present, the value of position gain is less important.

The K1 x TGT interaction is significant only at a velocity gain of zero. Table 7 contains the results of a

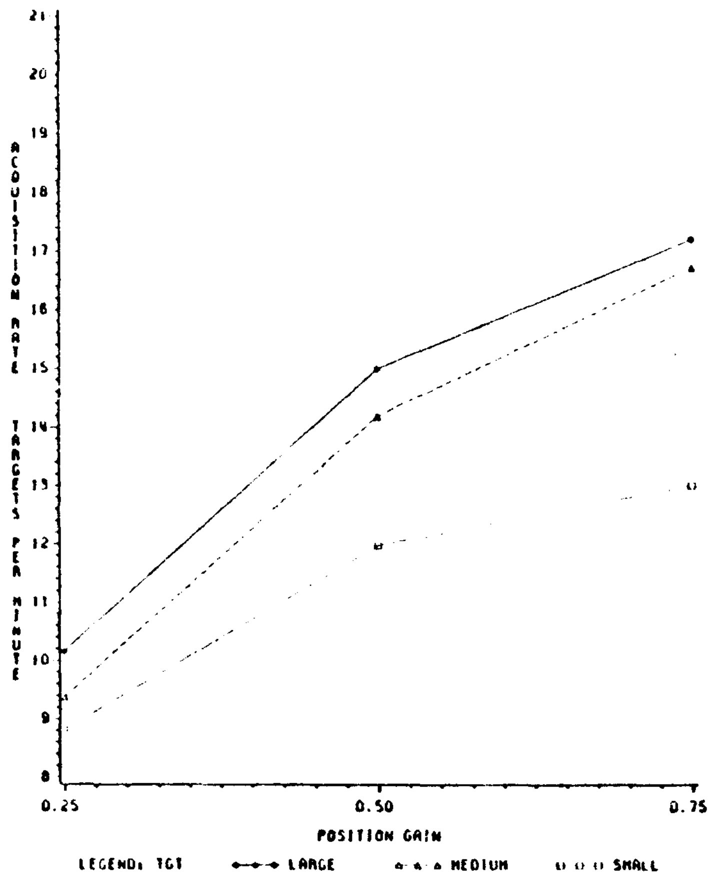
TABLE 5

Newman-Keuls Test Results for K2 x TGT Interaction for Acquisition Rate

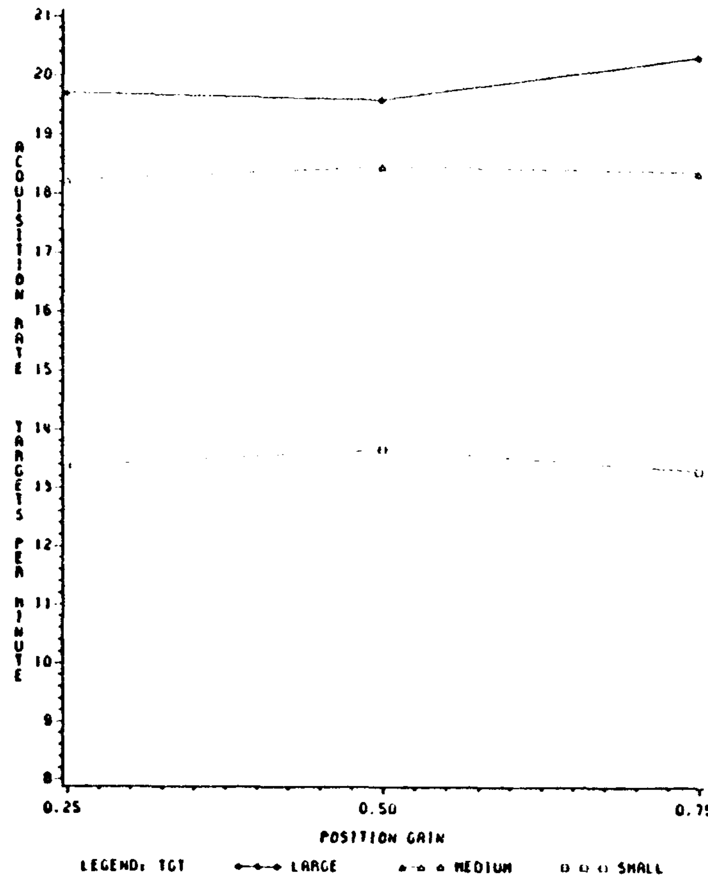
TGT	K2	Mean Rate	
high	0.3	10.03	A
high	0.0	11.27	B
high	0.2	12.09	C
high	0.1	13.43	D
med.	0.0	13.44	D
low	0.0	14.12	E
med.	0.3	15.51	F
med.	0.2	17.59	G
med.	0.1	18.34	H
low	0.3	18.37	H
low	0.2	19.44	I
low	0.1	19.87	I

Alpha level = 0.05.

Means with the same letter are not significantly different.

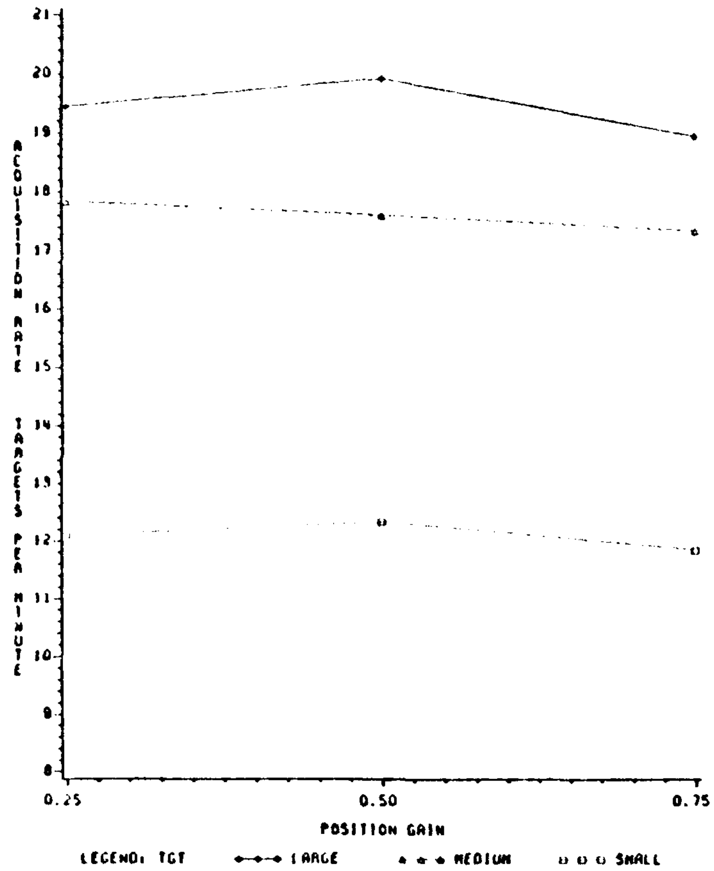


a. K1 x TGT interaction at K2 = 0.0

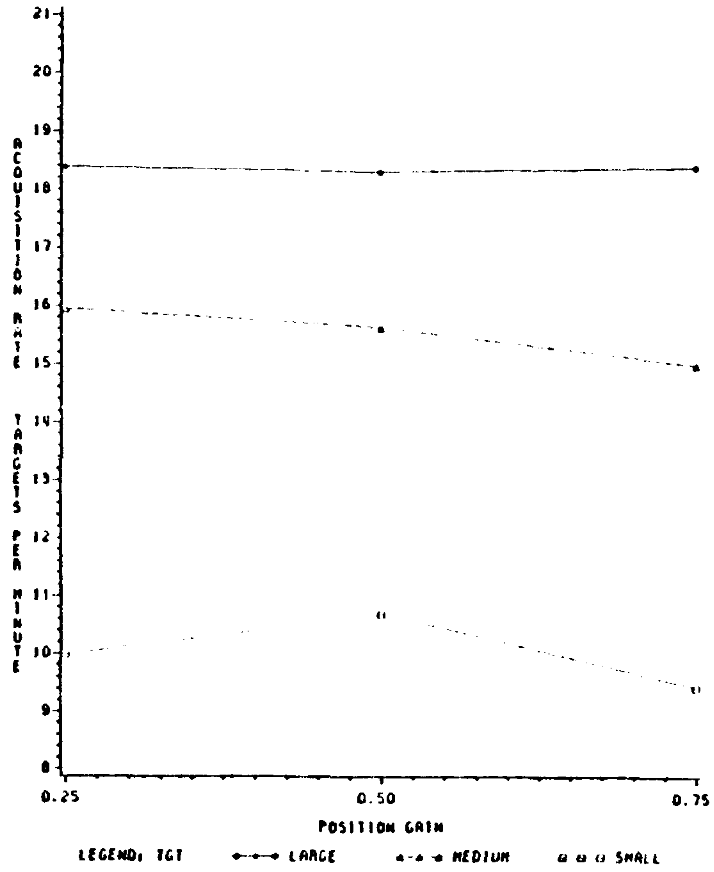


b. K1 x TGT interaction at K2 = 0.1

Figure 19: K1 x K2 x TGT interaction for acquisition rate.



a. K1 x TGT interaction at K2 = 0.2



d. K1 x TGT interaction at K2 = 0.3

Figure 19: K1 x K2 x TGT interaction for acquisition rate.

TABLE 6

Summary Table of the Individual Simple-Effects F-tests for Each Velocity Gain

Source	df	MS	F
Velocity Gain = 0.0			
K1	2	1081.47	286.86 *
TGT	2	239.20	63.44 *
K1 x TGT	4	27.85	7.39 *
Velocity Gain = 0.1			
K1	2	1.32	0.35
TGT	2	1219.19	323.58 *
K1 x TGT	4	2.99	0.79
Velocity Gain = 0.2			
K1	2	9.45	2.51
TGT	2	1580.44	419.21 *
K1 x TGT	4	1.67	0.44
Velocity Gain = 0.3			
K1	2	11.19	1.03
TGT	2	1938.70	5.14 *
K1 x TGT	4	5.73	1.52

* $p < 0.05$

TABLE 7

Newman-Keuls Test Results of K1 x TCT Interaction at K2 = 0.0 for Acquisition Rate

K1	TGT	Mean Rate	
0.25	high	8.83	A
0.25	med.	9.38	A B
0.25	low	10.16	B
0.50	high	11.97	C
0.75	high	13.00	D
0.50	med.	14.18	E
0.50	low	14.98	E
0.75	med.	16.72	F
0.75	low	17.21	F

Alpha level = 0.05.

Means with the same letter are not significantly different.

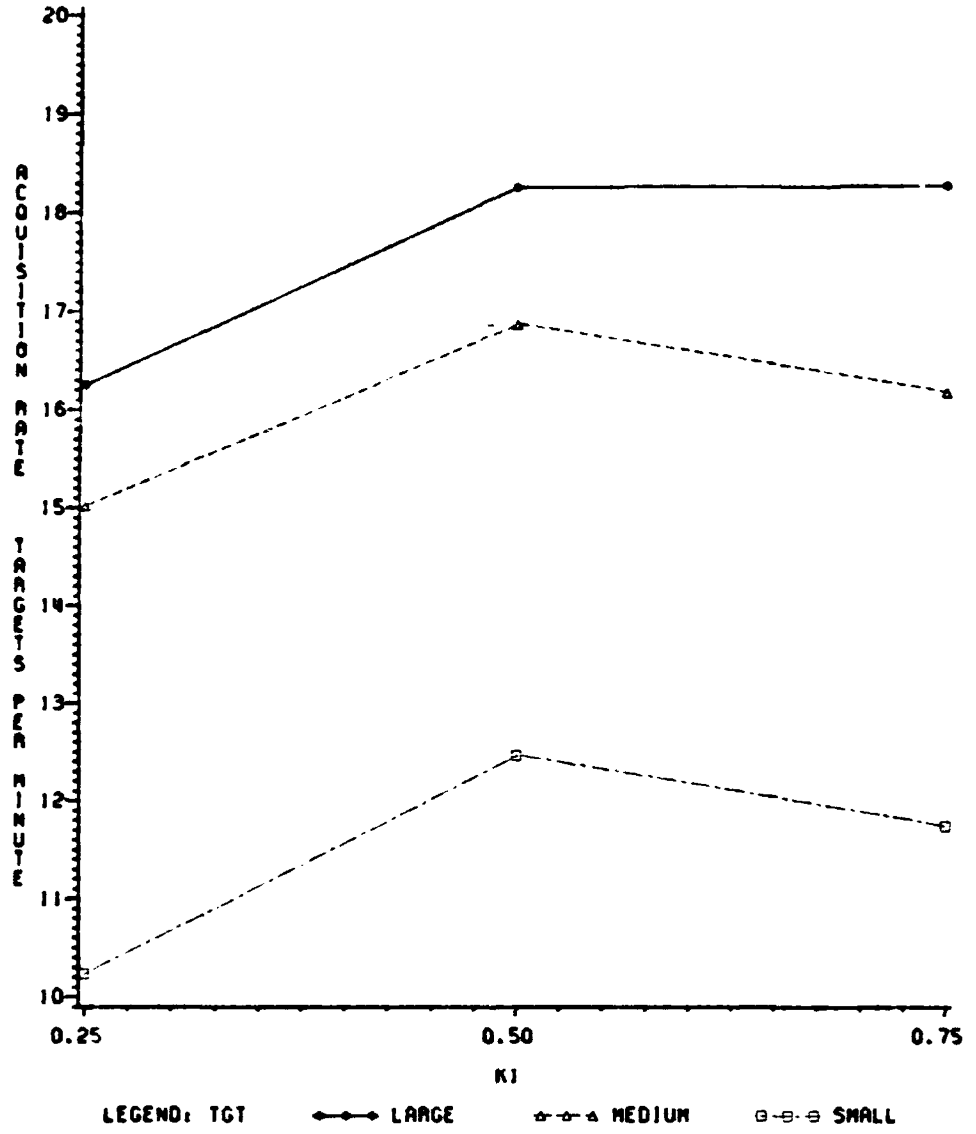
Newman-Keuls test for the K1 x TGT interaction at zero velocity gain. At zero velocity gain, the increase in target acquisition rate with increasing position gain (observed for all target sizes) begins to flatten for small targets as position gain becomes high. This suggests that target acquisition becomes difficult for small targets at high position gain.

The K1 x TS x TGT interaction is also significant (Figure 20). A simple-effects F test (Table 8) indicates that the main effect of position gain is significant for each tablet size. For the small and large tablet sizes, medium and high position gains are not significantly different but are significantly different from low position gain, whereas for the medium tablet size, low and medium position gains are not significantly different but were significantly different from high position gain.

The main effect of target size is significant for each tablet size. All levels of target size are significantly different for each tablet size.

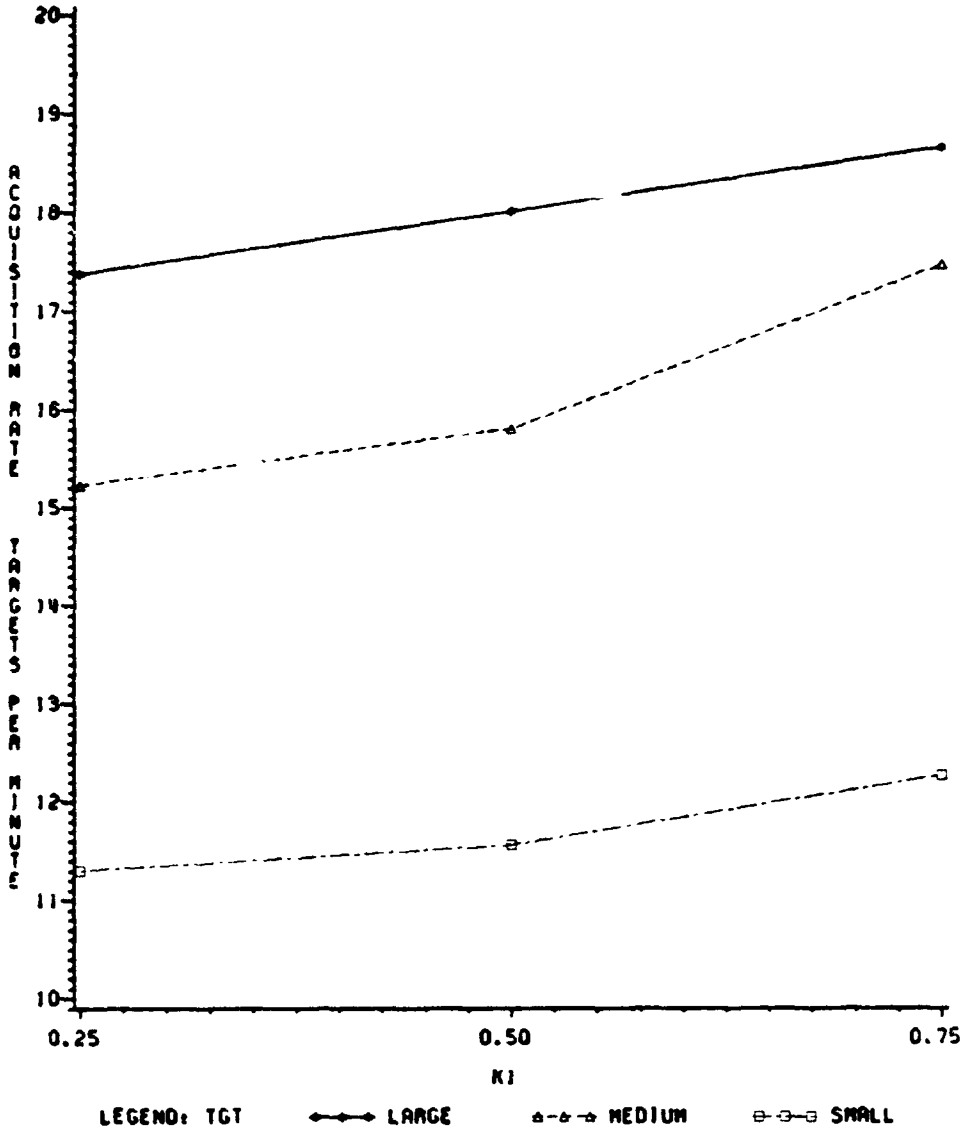
The K1 x TGT interaction is significant for the large tablet size. Tables 9 contains the results of a Newman-Keuls test for the large tablet size.

For the large tablet size, an increase from medium position gain to high position gain affects acquisition rate



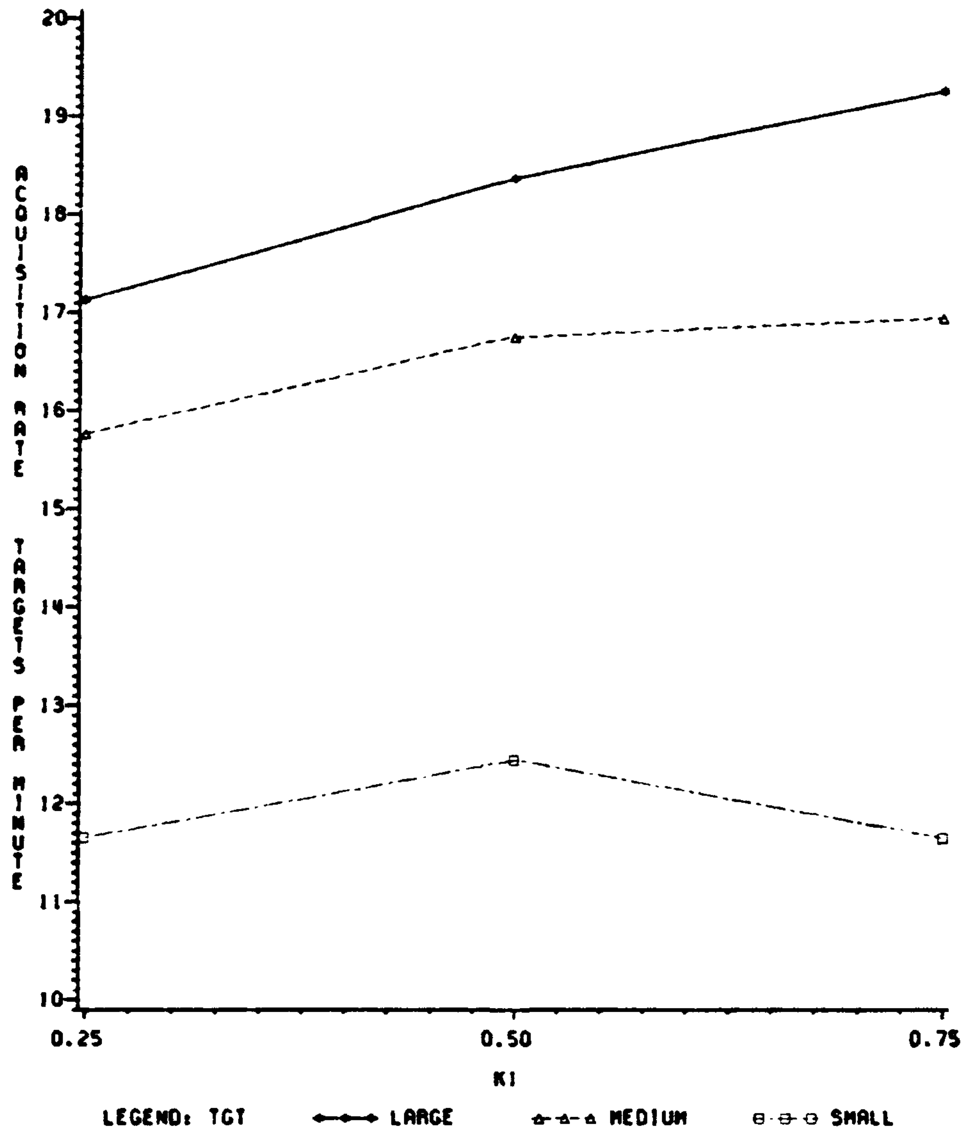
a. K1 x TGT interaction for small tablet size.

Figure 20: K1 x TS X TGT interaction for acquisition rate.



b. K1 x TGT interaction for medium tablet size.

Figure 20: K1 x TS X TGT interaction for acquisition rate.



c. K1 x TGT interaction for large tablet size.

Figure 20: K1 x TS X TGT interaction for acquisition rate.

TABLE 8

Summary Table of the Individual Simple-Effects F-tests for Each Target Size

Source	df	MS	F
Small Tablet Size			
K1	2	160.72	61.45 *
TGT	2	1448.03	553.70 *
K1 x TGT	4	3.20	1.26
Medium Tablet Size			
K1	2	81.89	31.31 *
TGT	2	1507.91	576.59 *
K1 x TGT	4	6.34	2.43
Large Tablet Size			
K1	2	52.55	20.09 *
TGT	2	1534.99	586.95 *
K1 x TGT	4	15.21	5.81 *

* $p < 0.05$

TABLE 9

Newman-Keuls Test Results of K1 x TGT Interaction for Large Tablet Size for Acquisition Rate

TGT	K1	Mean Rate	
high	0.75	11.65	A
	0.25	11.66	A
	0.50	12.45	B
med.	0.25	15.76	C
	0.50	16.74	D
	0.75	16.93	D
low	0.25	17.14	D
	0.50	18.36	E
	0.75	19.25	F

Alpha level = 0.05.

Means with the same letter are not significantly different.

differently depending on target size. For the large target size, acquisition rate increases as position gain increases from medium to high position gain. For the medium target size, acquisition rate remains constant as position gain increases from medium to high. For the small target size, acquisition rate decreases as position gain increases from medium to high.

Target Entries

An ANOVA (Table 10) indicates that the main effect of position gain (K1) on the number of target entries prior to confirmation is statistically significant. A Newman-Keuls test shows that a position gain of 0.75 is significantly different from position gains of 0.25 and 0.50 ($p < 0.05$). As expected, low position gains enhance fine positioning; i.e., low position gains result in fewer entries into the target prior to confirmation (Figure 21).

There is a significant main effect of velocity gain (K2). A Newman-Keuls test indicates that all levels of velocity gain are significantly different from each other ($p < 0.05$), with lower levels resulting in fewer target entries (Figure 22). This result indicates that any non-zero level of velocity gain increased the difficulty of the fine positioning aspect of the target acquisition task.

TABLE 10

Analysis of Variance Summary Table for Target Entries

Source	df	MS	F	p
Between-Subjects				
Subjects (S)	11	1.11		
Within-Subjects				
K1	2	0.71	9.55	0.0010
K1 x S	22	0.07		
K2	3	19.20	145.60	0.0001
K2 x S	33	0.13		
TABLET SIZE (TS)	2	0.03	0.16	0.8541
TS x S	22	0.22		
TARGET SIZE (TGT)	2	17.17	107.47	0.0001
TGT x S	22	0.16		
K1 x K2	6	0.04	0.49	0.8155
K1 x K2 x S	66	0.08		
K1 x TS	4	0.21	1.72	0.1622
K1 x TS x S	44	0.12		
K1 x TGT	4	0.06	0.99	0.4245
K1 x TGT x S	44	0.06		
K2 x TS	6	0.17	1.74	0.1246
K2 x TS x S	66	0.10		
K2 x TGT	6	1.75	28.22	0.0010
K2 x TGT x S	66	0.06		
TS x TGT	4	0.09	1.41	0.2451
TS x TGT x S	44	0.07		
K1 x K2 x TS	12	0.11	1.22	0.2761
K1 x K2 x TS x S	132	0.09		

TABLE 10, Continued

K1 x K2 x TGT	12	0.08	1.30	0.2259
K1 x K2 x TGT x S	132	0.06		
K1 x TS x TGT	8	0.03	0.63	0.7498
K1 x TS x TGT x S	88	0.05		
K2 x TS x TGT	12	0.08	1.25	0.2587
K2 x TS x TGT x S	132	0.06		
K1 x K2 x TS x TGT	24	0.06	1.35	0.1338
K1 x K2 x TS x TGT	264	0.04		
Total	1295			

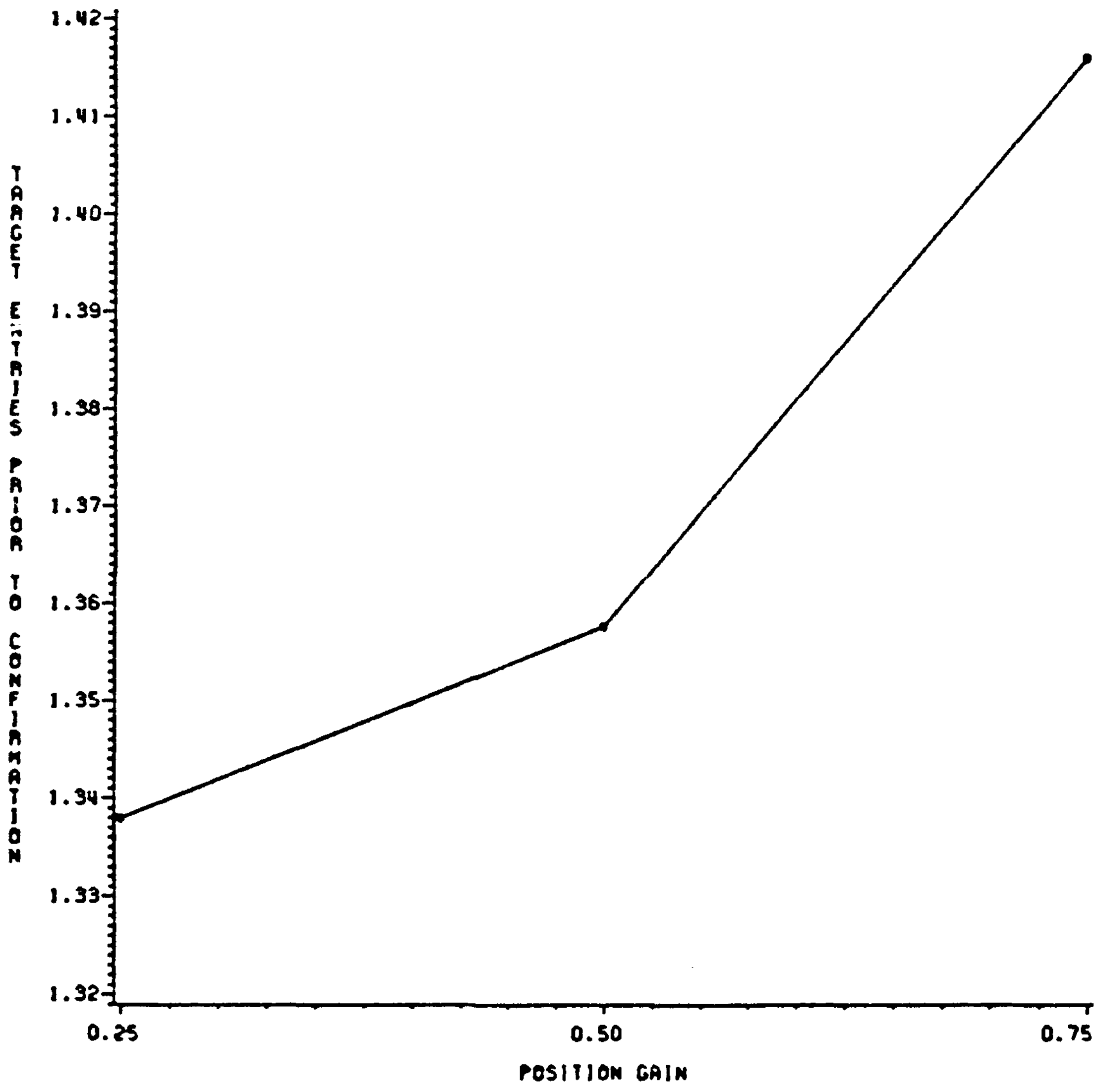


Figure 21: Position gain main effect for target entries.

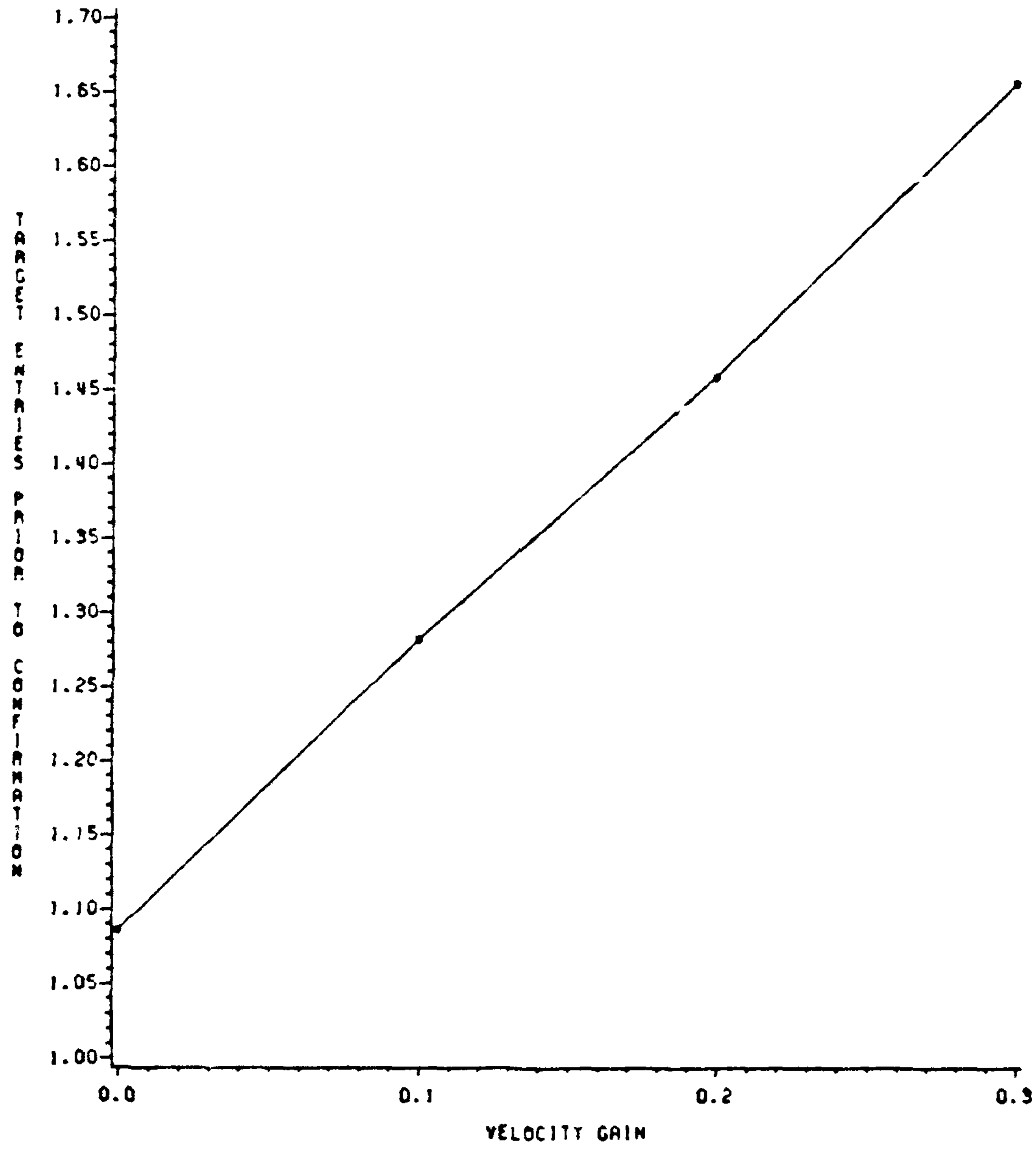


Figure 22: Velocity gain main effect for target entries.

The main effect of target size is significant. A Newman-Keuls test shows that all levels of target size are significantly different ($p < 0.05$), with large targets having the fewest entries into a target and small targets having the most entries into a target (Figure 23). Thus, fine positioning becomes more difficult as the target area becomes smaller.

The only significant interaction for the target entries dependent variable is the K2 x TGT interaction. Target entries increase as velocity gain increases for all target sizes. However, as velocity gain increases, the increase in target entries for the small targets is greater than the increase in target entries for the medium and large targets (Figure 24). Thus, velocity gain of 0.3 and small target size interact to substantially increase the difficulty of fine positioning. Table 11 contains the results of a Newman-Keuls test.

Percentage Error

Error rates across the different conditions tested are relatively low, not exceeding three percent. Nonetheless, an ANOVA (Table 12) revealed a few significant effects. The main effect of the additive velocity component (K2) is significant. A Newman-Keuls test shows that the velocity

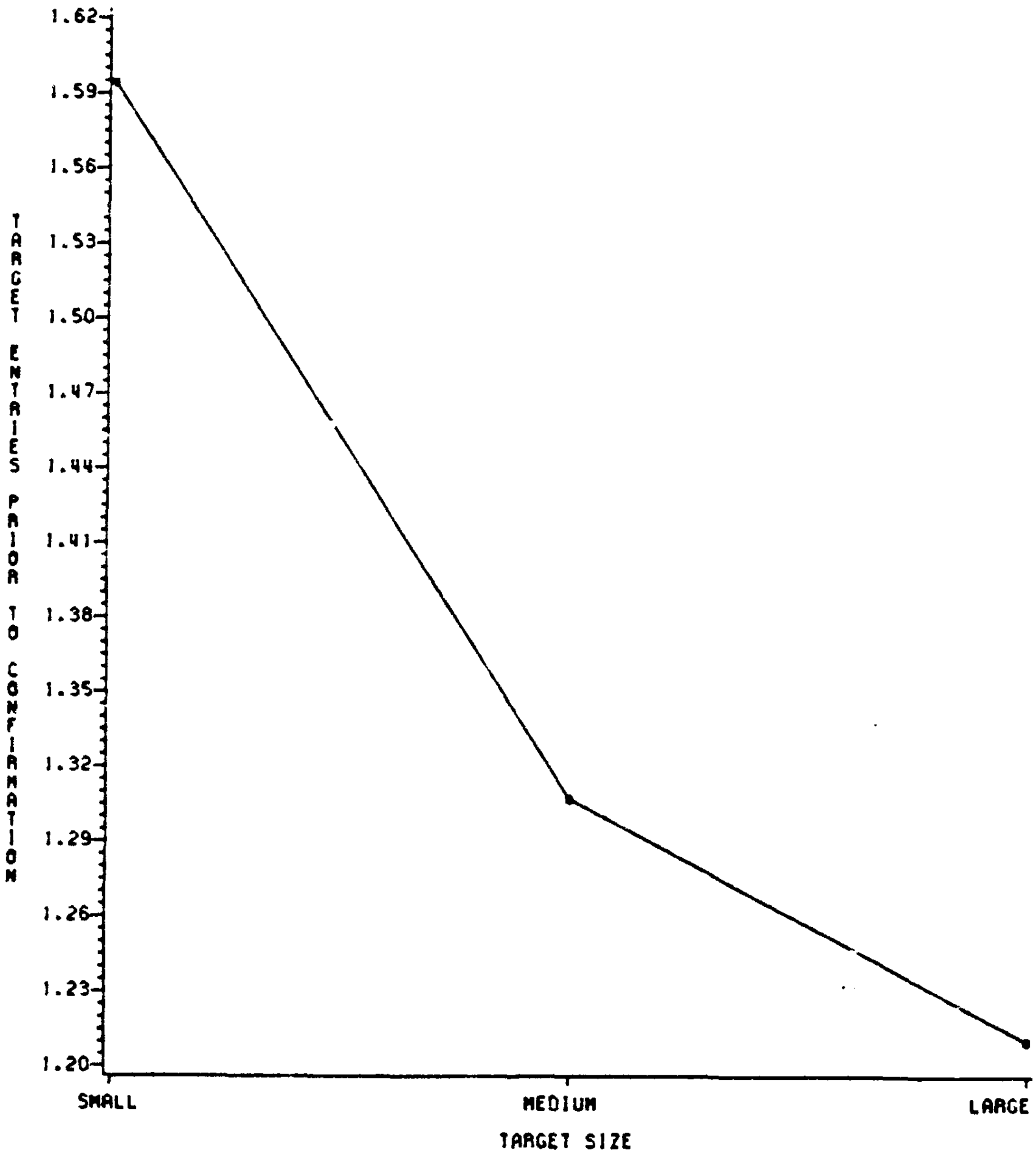


Figure 23: Target size main effect for target entries.

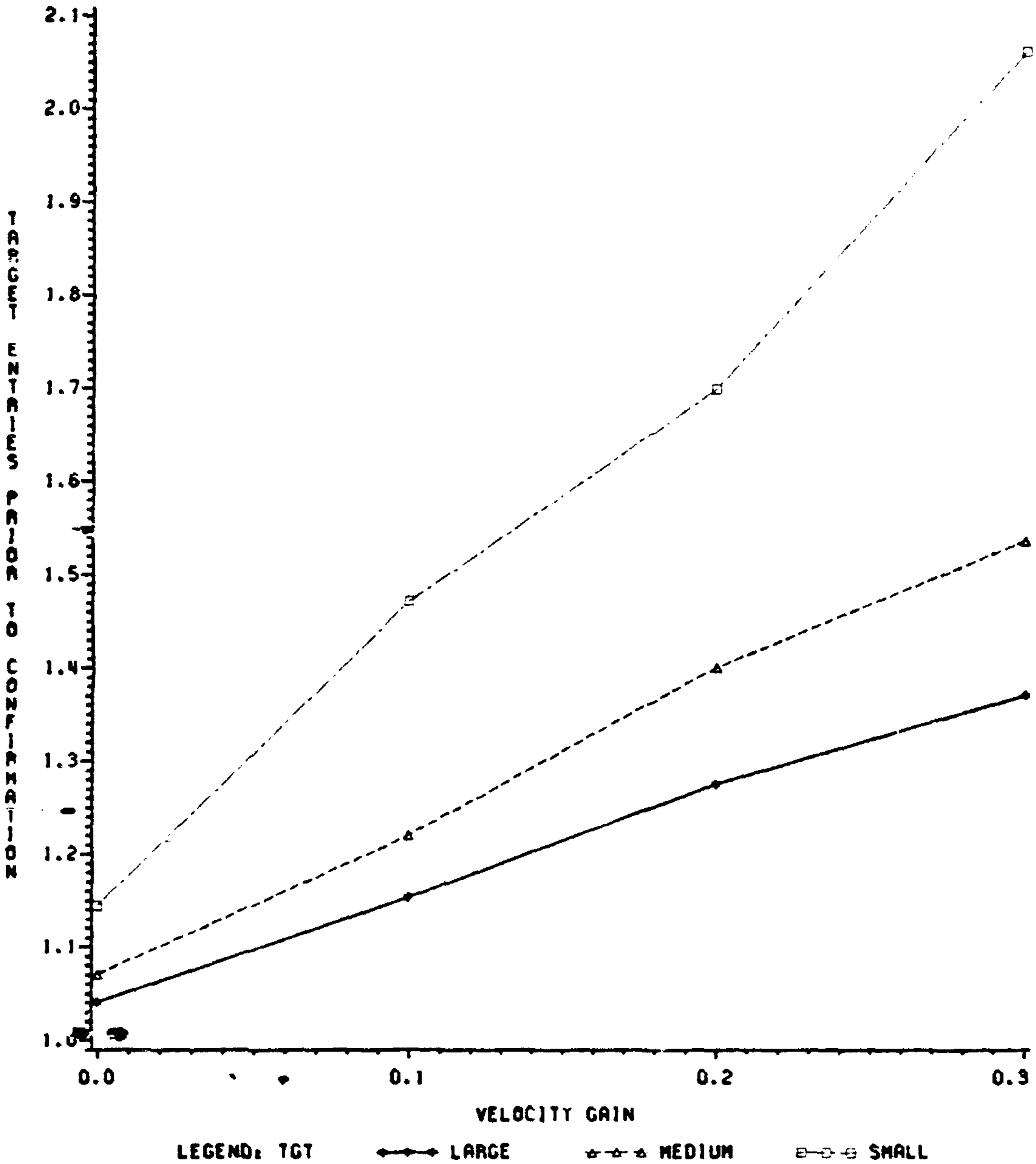


Figure 24: K2 x TGT interaction for target entries.

TABLE 11

Newman-Keuls Test Results for K2 x TGT Interaction for Target Entries

K2	TGT	Mean Entries	
0.0	low	1.04	A
0.0	med.	1.07	A
0.1	low	1.14	B
0.0	high	1.15	B
0.1	med.	1.22	C
0.2	low	1.27	C
0.3	low	1.37	D
0.2	med.	1.40	D
0.1	high	1.47	E
0.3	med.	1.53	E
0.2	high	1.69	F
0.3	high	2.06	G

Alpha level = 0.05.

Means with the same letter are not significantly different.

TABLE 12

Analysis of Variance Summary Table for Percentage Error

Source	df	MS	F	p
Between-Subjects				
Subjects (S)	11	67.84		
Within-Subjects				
K1	2	30.20	1.55	0.2341
K1 x S	22	19.46		
K2	3	48.88	3.07	0.0412
K2 x S	33	15.92		
TABLET SIZE (TS)	2	11.97	0.53	0.5969
TS x S	22	22.66		
TARGET SIZE (TGT)	2	60.64	4.13	0.0301
TGT x S	22	14.70		
K1 x K2	6	10.07	0.48	0.8212
K1 x K2 x S	66	21.00		
K1 x TS	4	2.94	0.13	0.9719
K1 x TS x S	44	23.11		
K1 x TGT	4	25.56	1.77	0.1523
K1 x TGT x S	44	14.45		
K2 x TS	6	19.75	1.19	0.3218
K2 x TS x S	66	16.58		
K2 x TGT	6	17.38	1.31	0.2646
K2 x TGT x S	66	13.26		
TS x TGT	4	27.57	1.59	0.1945
TS x TGT x S	44	17.37		
K1 x K2 x TS	12	29.23	1.94	0.0347
K1 x K2 x TS x S	132	15.05		

TABLE 12, Continued

K1 x K2 x TGT	12	20.01	1.23	0.2678
K1 x K2 x TGT x S	132	16.24		
K1 x TS x TGT	8	22.89	1.98	0.0585
K1 x TS x TGT x S	88	11.58		
K2 x TS x TGT	12	19.13	1.39	0.1759
K2 x TS x TGT x S	132	13.71		
K1 x K2 x TS x TGT	24	20.08	1.34	0.1367
K1 x K2 x TS x TGT x S	264	14.97		
Total	1295			

components of 0.1, 0.2, and 0.3 are not significantly different from each other but are significantly different from a velocity component of 0.0 ($p < 0.05$). Similarly, velocity components of 0.0, 0.1, and 0.2 are not significantly different from each other but are significantly different from a velocity component of 0.3 (Figure 25).

The main effect of target size is also significant. A Newman-Keuls test indicates that the error rates for the small and medium targets are not significantly different, but are significantly different from that for large targets ($p < 0.05$). Likewise, the error rate of the medium and large targets are not significantly different, but are significantly different from small targets (Figure 26).

The K1 x K2 x TS interaction is significant. A simple-effects F test (Table 13) indicated that the effect of K2 is significant for the small tablet size, but not for the other tablet sizes (Figure 27). For the small tablet size, a Newman-Keuls test shows that while the error rates for K2 values of 0.1, 0.2 and 0.3 are not significantly different, they are significantly different from the error rate for the K2 value of 0.0. Similarly, the error rates for K2 values of 0.0, 0.1 and 0.3 are not significantly different, but are significantly different from the error

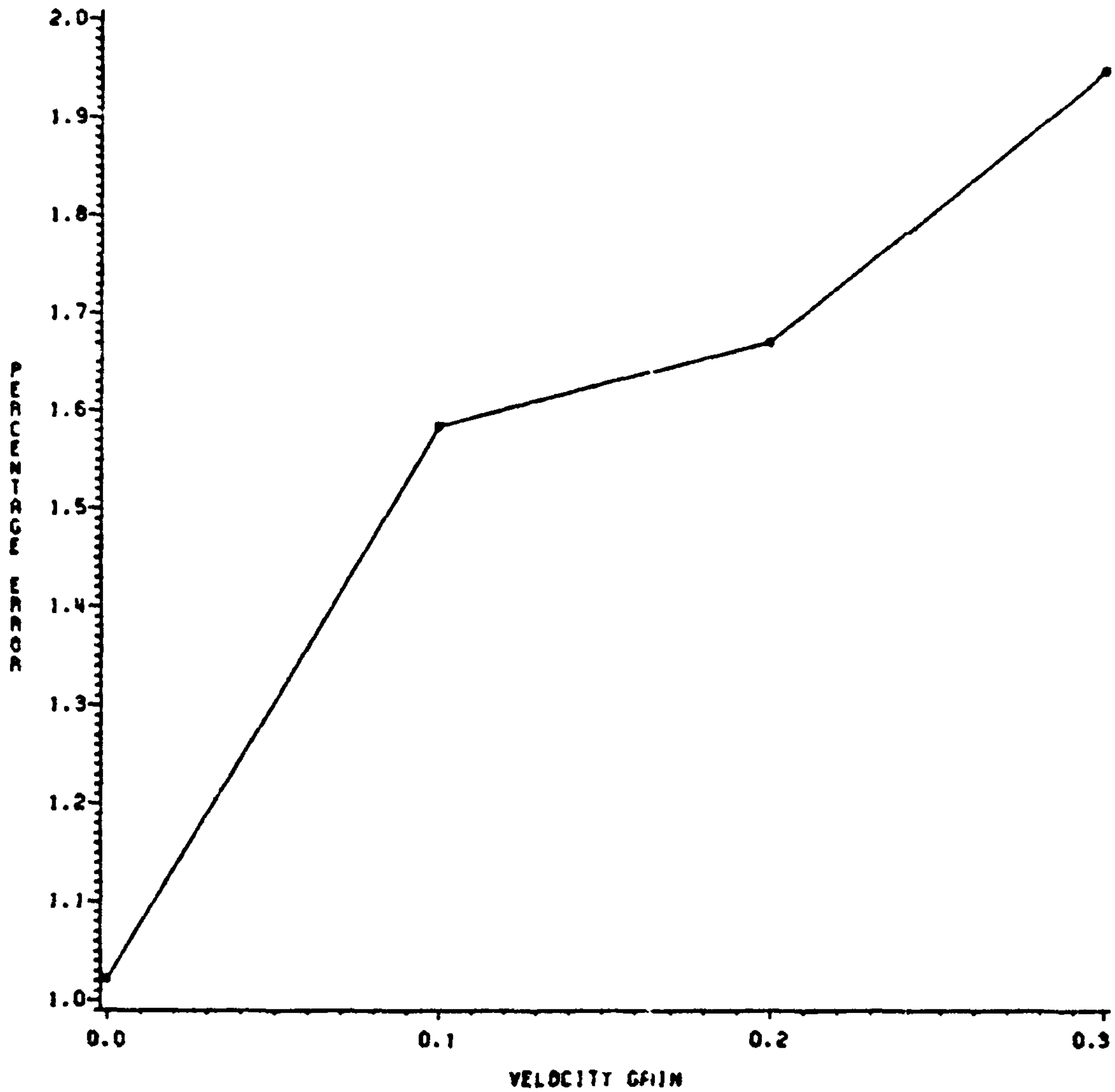


Figure 25: Velocity gain main effect for percentage error.

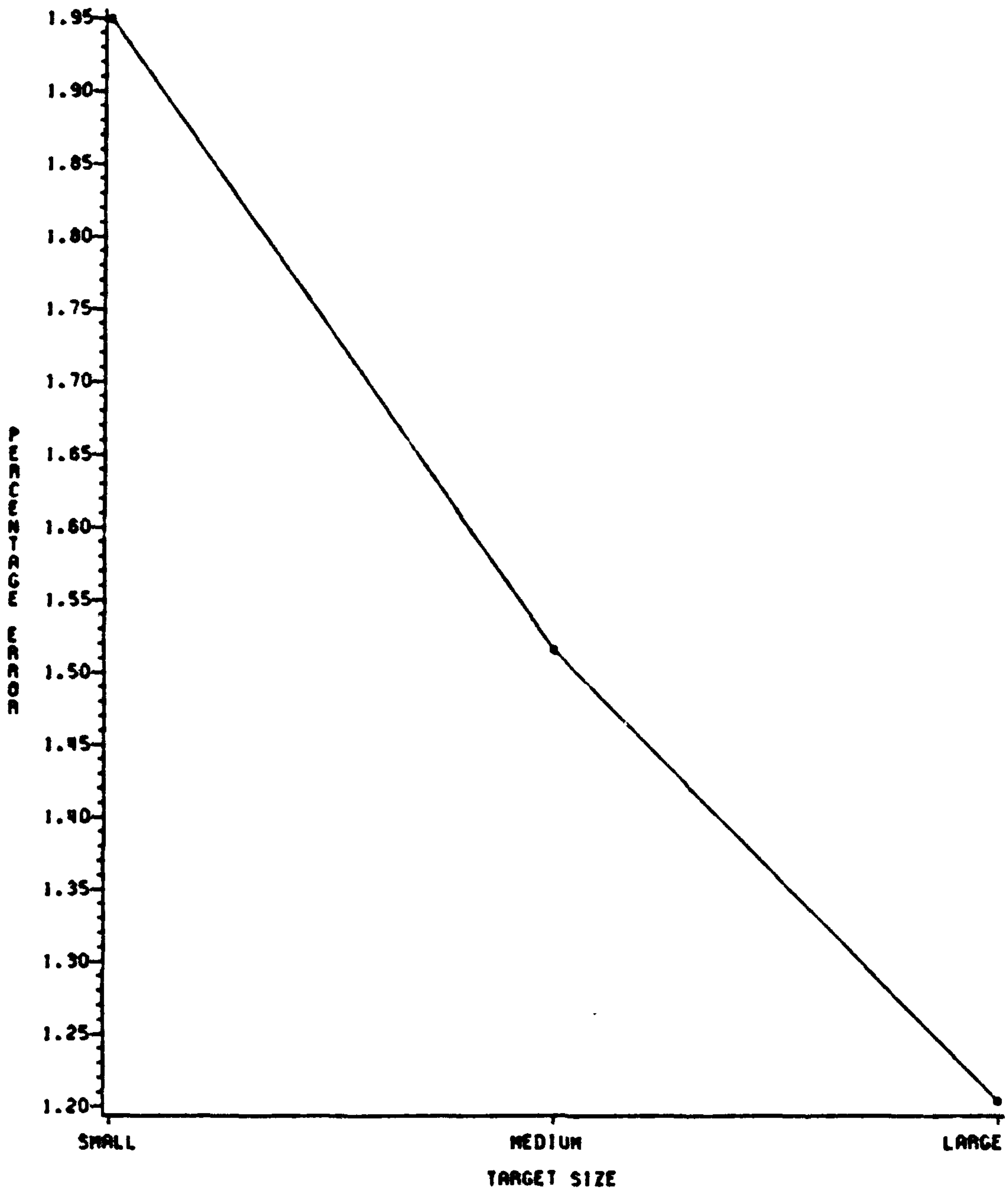


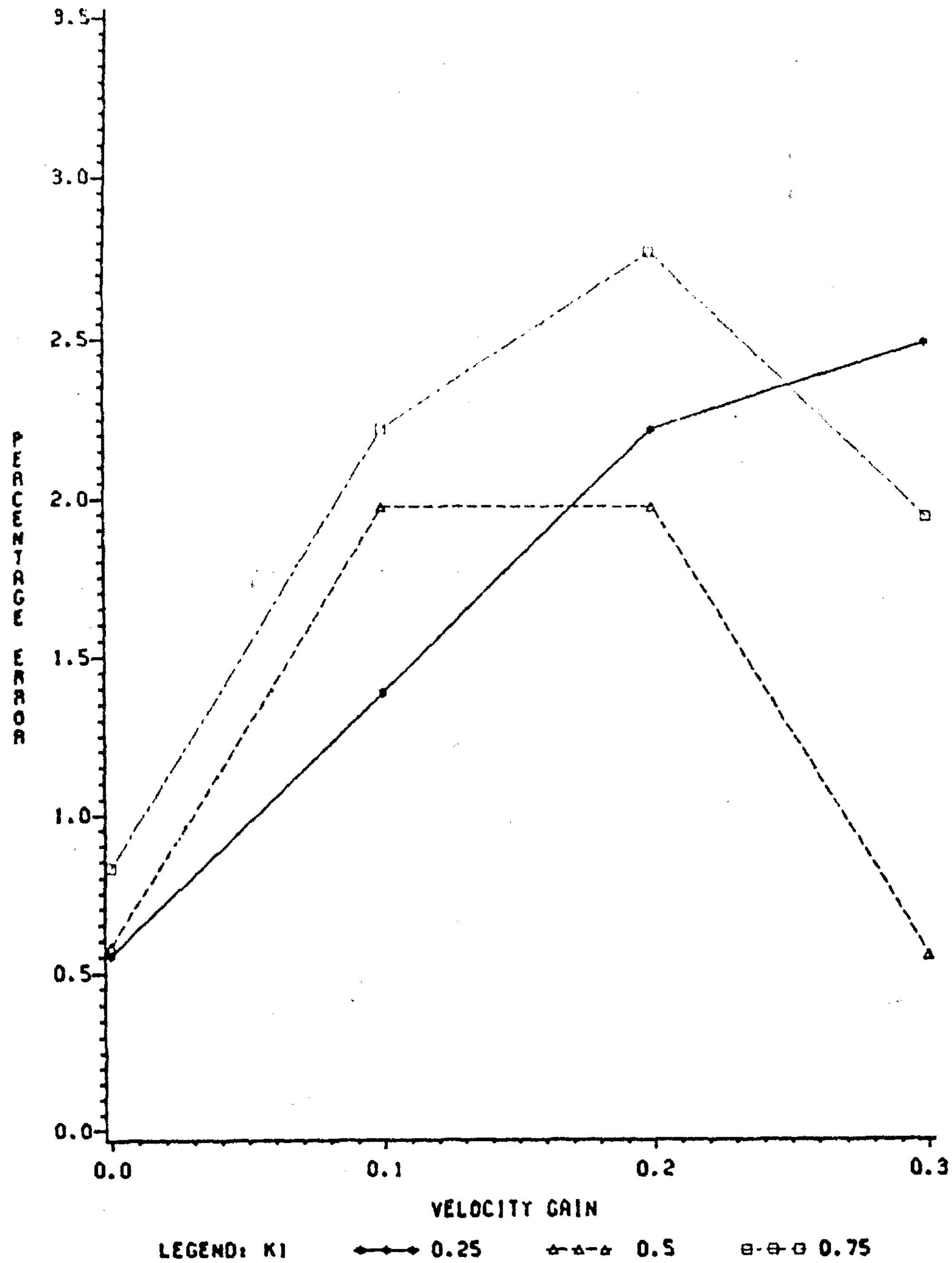
Figure 26: Target size main effect for percentage error.

TABLE 13

Summary Table of the Individual Simple-Effects F-tests for Each Tablet Size

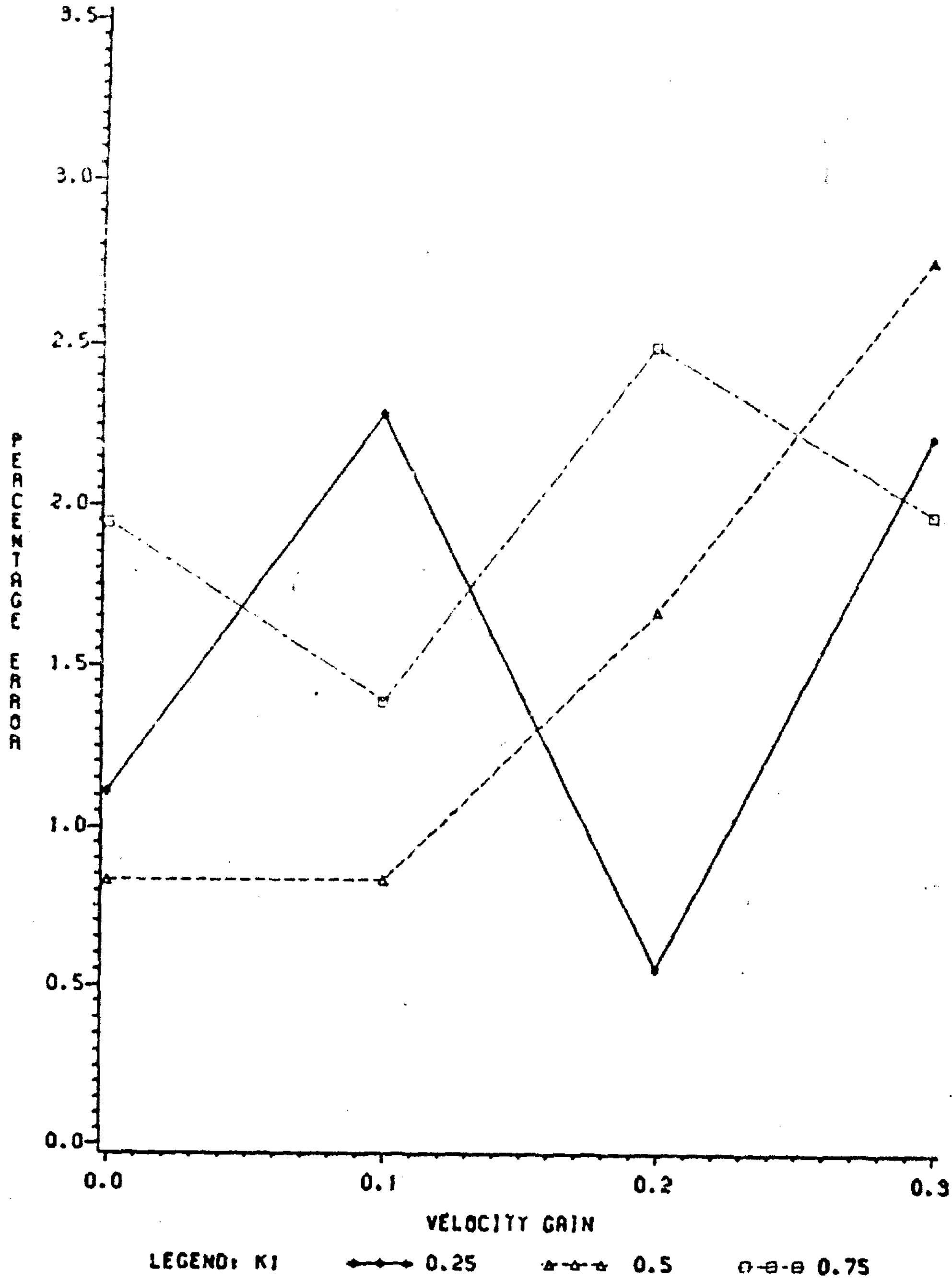
Source	df	MS	F
Small Tablet Size			
K1	2	16.39	1.09
K2	3	53.36	3.55 *
K1 x K2	6	11.08	0.74
Medium Tablet Size			
K1	2	8.34	0.55
K2	3	21.82	1.45
K1 x K2	6	21.11	1.40
Large Tablet Size			
K1	2	11.34	0.75
K2	3	13.19	0.87
K1 x K2	6	36.34	2.41

* $p < 0.05$



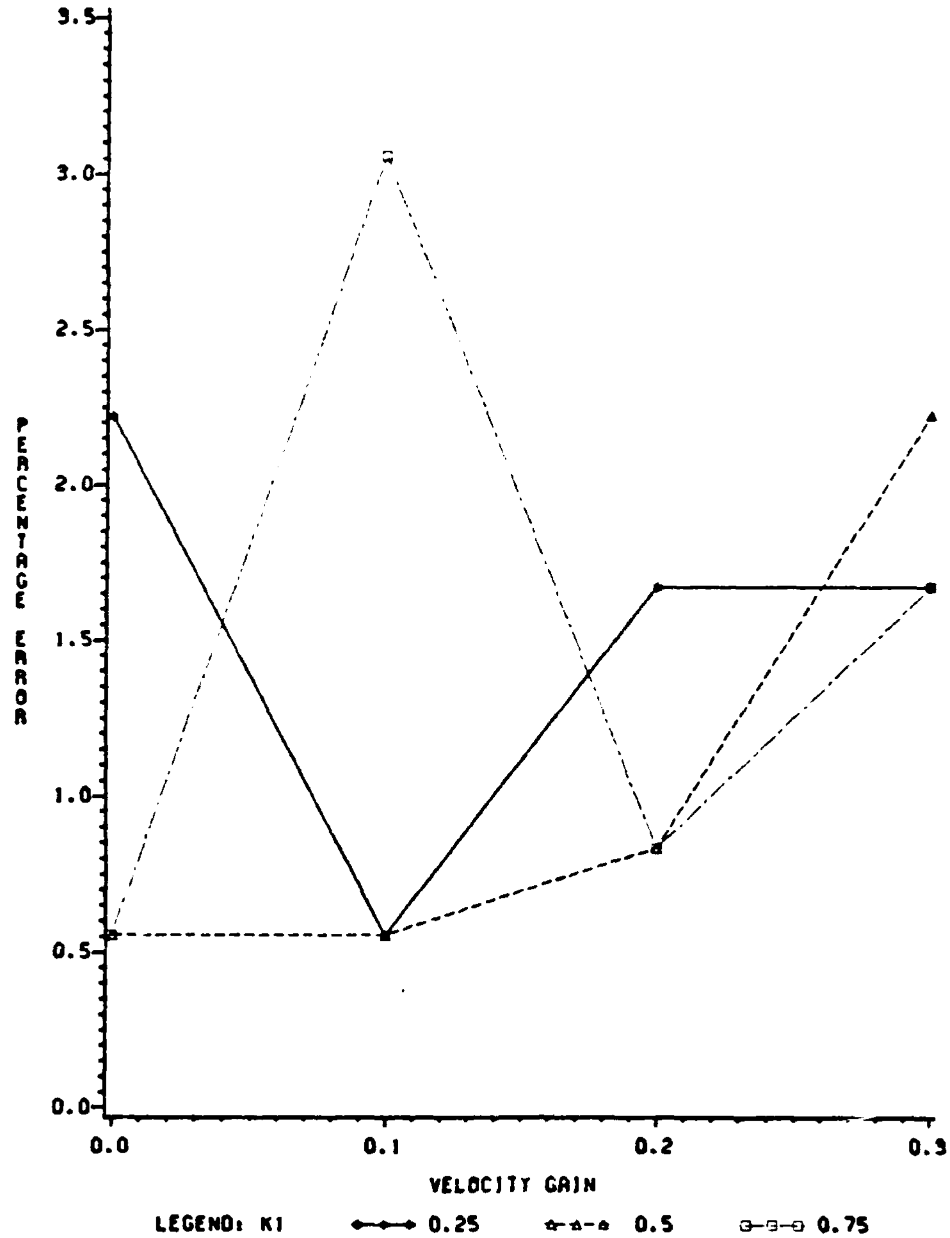
a. K1 x K2 interaction for small tablet size.

Figure 27: K1 x K2 x TS interaction for percentage error.



b. K1 x K2 interaction for medium tablet size.

Figure 27: K1 x K2 x TS interaction for percentage error.



c. K1 x K2 interaction for large tablet size.

Figure 27: K1 x K2 x TS interaction for percentage error.

rate for the K2 value of 0.2. That the 0.2 velocity gain would result in the highest error rate for the small tablet size is surprising; the main effect of velocity gain on error rate suggests that error rate tends to increase with velocity gain. the higher the velocity gain, the more human performance deteriorates. It may be possible that high velocity gain on the small tablet created such difficulty for subjects that they took extra care and time to protect against errors in this condition. Thus, the dropoff in error rate at the velocity gain of 0.3 may be a reflection of a speed-accuracy trade-off in which speed was traded by subjects for accuracy (Figure 13).

Movement Time

To further investigate the effect of position gain and velocity gain on acquisition rate, an ANOVA was conducted on movement time data. The factor movement type was added to the ANOVA. Movement type was either gross movement or fine positioning. Gross movement time was defined as the time from the start of a trial to the first entry into the target. Fine positioning time was defined as the time from first entry into the target to final entry into the target. Thus, under this definition, fine positioning time was non-zero only when there were multiple entries into the

target. The decision as to when gross movement ends and fine positioning begins is rather arbitrary. In fact, detailed investigation of the human operator's control input would probably reveal a gradual transition from gross movement to fine positioning. The definitions noted above represent one dichotomization of the target acquisition task. They have the advantage of being measurable in a simple and unambiguous fashion.

An ANOVA for movement time (Table 14) indicated that the main effects of position gain, velocity gain, target size, and movement type are significant. The low position gain results in significantly slower gross movement time than do the medium or high position gains (Figure 28).

All levels of velocity gain are significantly different with a velocity gain of 0.1 yielding the fastest movement time (Figure 29). Non-zero velocity gains result in significantly faster movement time than zero velocity gain. These results indicate that velocity gain can be adjusted to reduce movement time.

All target sizes are significantly different from each other (Figure 30). Movement time is slowest for small targets and fastest for large targets.

As expected, gross movement time is significantly slower than fine movement time (Figure 31).

TABLE 14

Analysis of Variance Summary Table for Movement Time Data

Source	df	MS	F	p
Between-Subjects				
Subjects (S)	11	8.11		
Within-Subjects				
K1	2	23.40	43.82	0.0001
K1 x S	22	0.53		
K2	3	67.76	110.36	0.0001
K2 x S	33	0.61		
TABLET SIZE (TS)	2	1.91	0.53	0.5957
TS x S	22	3.60		
TARGET SIZE (TGT)	2	165.99	204.65	0.0001
TGT x S	22	0.81		
MOVEMENT TYPE (MT)	1	4160.89	765.39	0.0001
TGT x S	11	5.44		
K1 x K2	6	27.88	64.43	0.0001
K1 x K2 x S	66	0.43		
K1 x TS	4	1.57	3.01	0.0281
K1 x TS x S	44	0.52		
K1 x TGT	4	0.98	2.05	0.1038
K1 x TGT x S	44	0.48		
K2 x TS	6	0.27	0.58	0.7468
K2 x TS x S	66	0.46		
K2 x TGT	6	13.22	52.62	0.0001
K2 x TGT x S	66	0.25		
TS x TGT	4	0.39	0.82	0.5208
TS x TGT x S	44	0.47		

TABLE 14, Continued

K1 x MT	2	36.48	66.95	0.0001
K1 x MT x S	22	0.54		
K2 x MT	3	190.83	488.97	0.0001
K2 x MT x S	33	0.39		
TS x MT	2	1.27	1.17	0.3293
TS x MT x S	22	1.09		
TGT x MT	2	3.34	11.01	0.0005
TGT x MT x S	22	0.30		
K1 x K2 x TS	12	0.34	0.71	0.7440
K1 x K2 x TS x S	132	0.49		
K1 x K2 x TGT	12	0.53	2.18	0.0160
K1 x K2 x TGT x S	132	0.31		
K1 x TS x TGT	8	0.52	2.33	0.0255
K1 x TS x TGT x S	88	0.22		
K2 x TS x TGT	12	0.26	0.83	0.6198
K2 x TS x TGT x S	132	0.31		
K1 x K2 x MT	6	24.51	89.92	0.0001
K1 x K2 x MT x S	66	0.27		
K1 x TS x MT	4	0.60	1.39	0.2545
K1 x TS x MT x S	44	0.43		
K1 x TGT x MT	4	0.14	0.65	0.6267
K1 x TGT x MT x S	44	0.22		
K2 x TGT x MT	6	1.11	5.90	0.0001
K2 x TGT x MT x S	66	0.19		
K2 x TS x MT	6	0.71	2.00	0.0784
K2 x TS x MT x S	66	0.36		
TS x TGT x MT	4	0.05	0.16	0.9568
TS x TGT x MT x S	44	0.30		
K1 x K2 x TS x TGT	24	0.26	1.27	0.1874
K1 x K2 x TS x TGT x S	264	0.20		
K1 x K2 x TS x MT	12	0.49	1.00	0.5000
K1 x K2 x TS x MT x S	132	0.26		

TABLE 14, Continued

K1 x K2 x TGT x MT	12	0.19	1.00	0.5000
K1 x K2 x TGT x MT x S	132	0.23		
K1 x TS x TGT x MT	8	0.32	1.00	0.5000
K1 x TS x TGT x MT x S	88	0.22		
K2 x TS x TGT x MT	12	0.14	1.00	0.5000
K2 x TS x TGT x MT x S	132	0.19		
K1 x K2 x TS x TGT x MT	24	0.31	1.79	0.0149
K1 x K2 x TS x TGT x MT x S	264	0.17		
Total	2591			

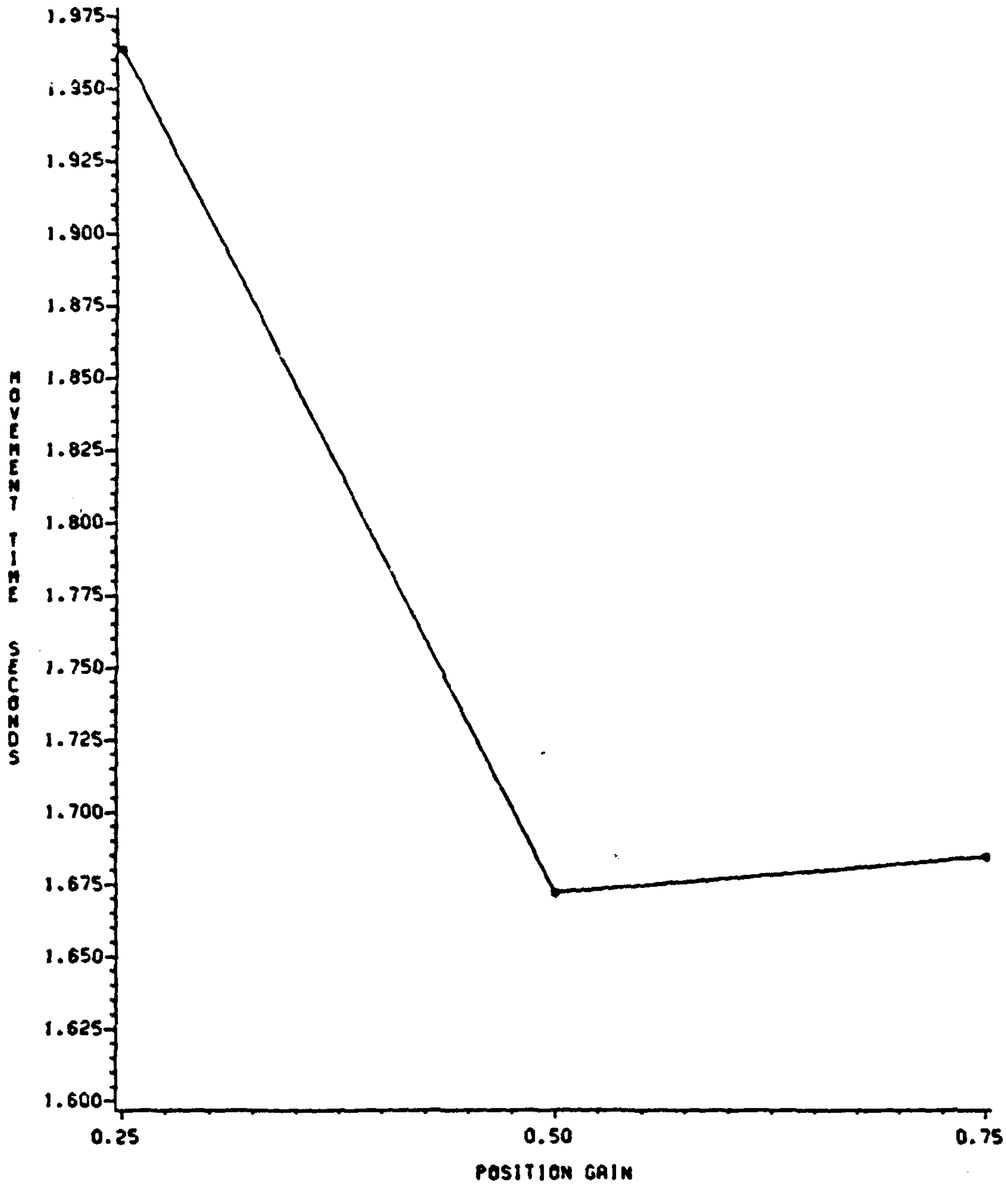


Figure 28: Position gain main effect for movement time.

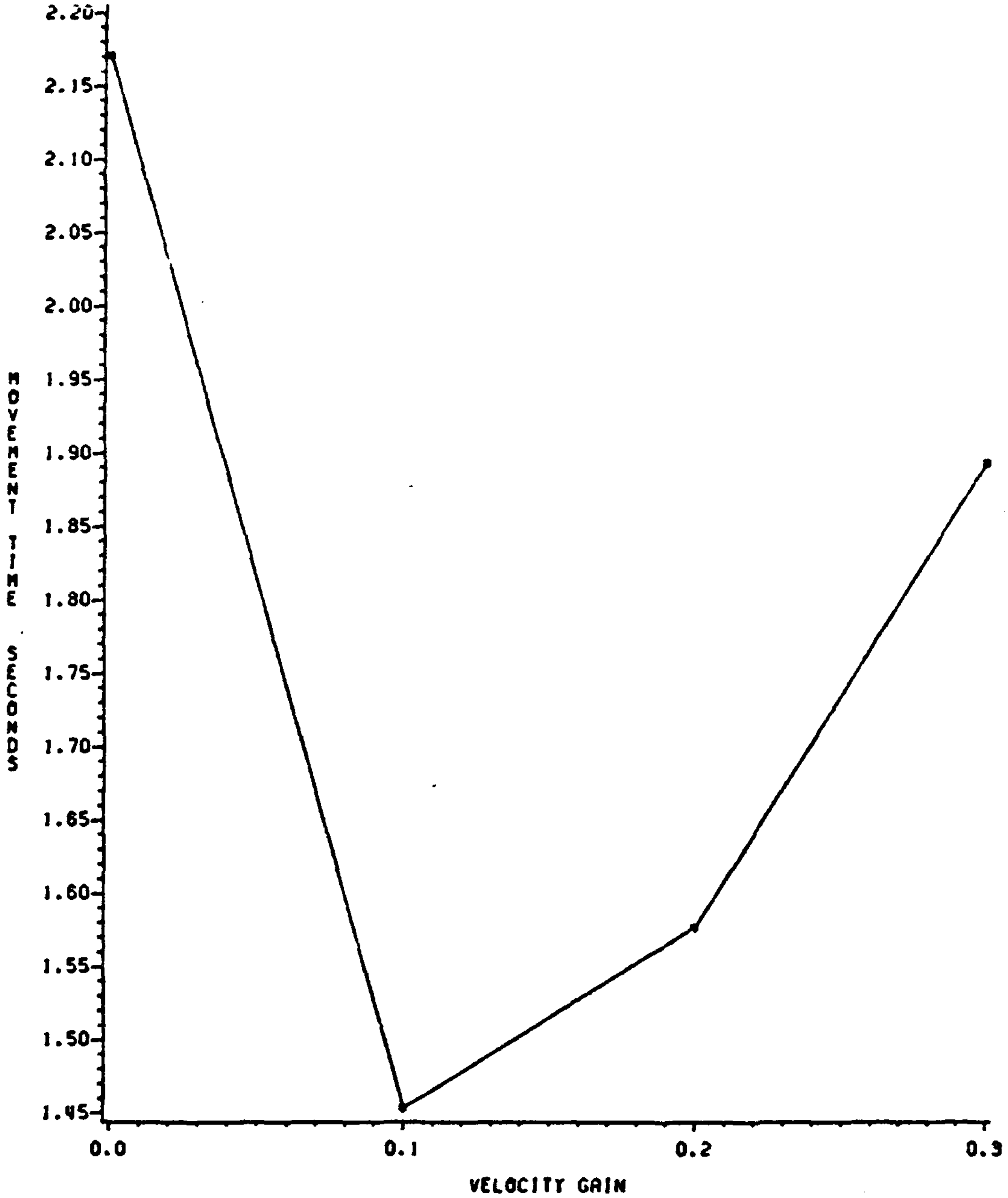


Figure 29: Velocity gain main effect for movement time.

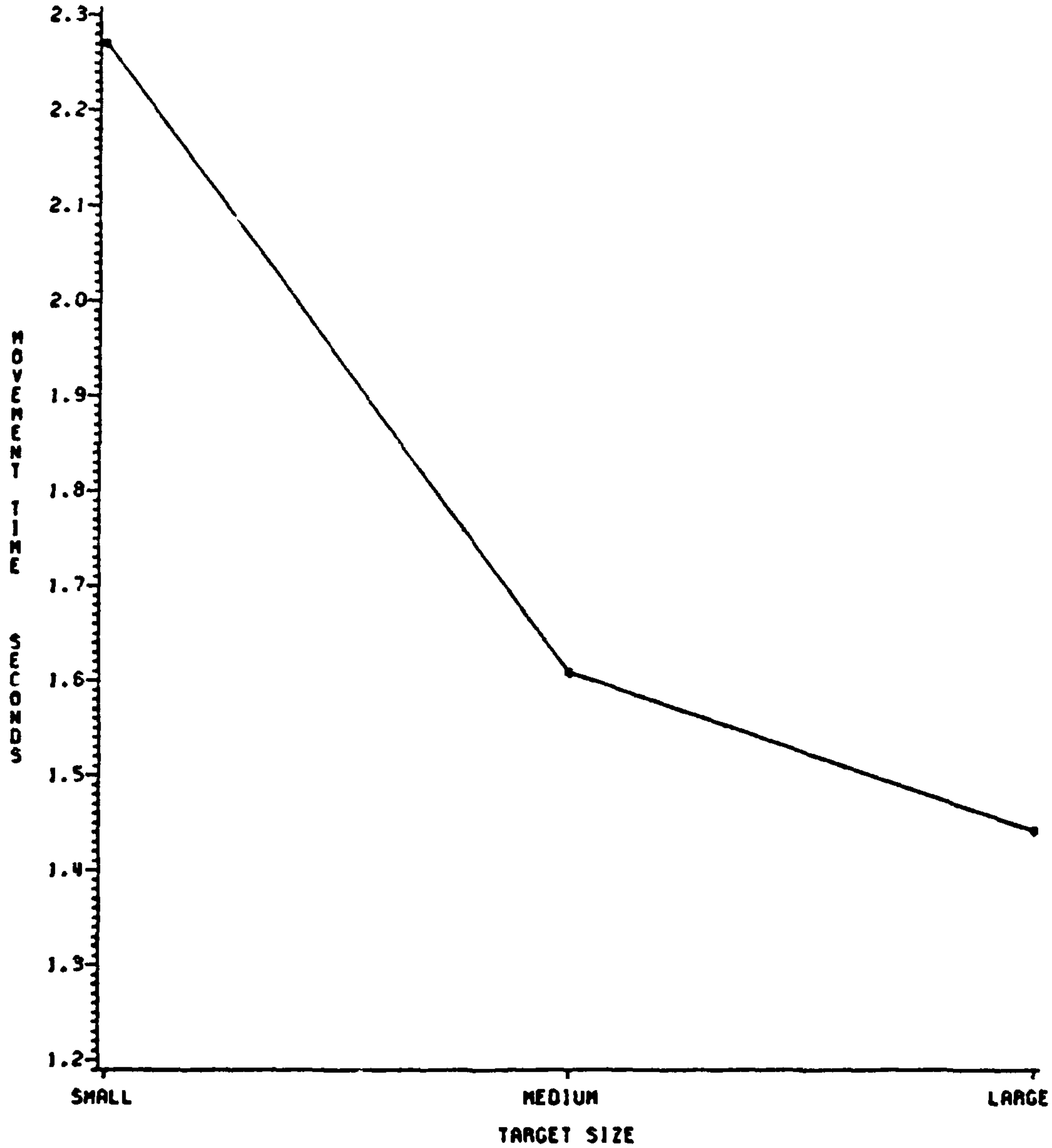


Figure 30: Target size main effect for movement time.

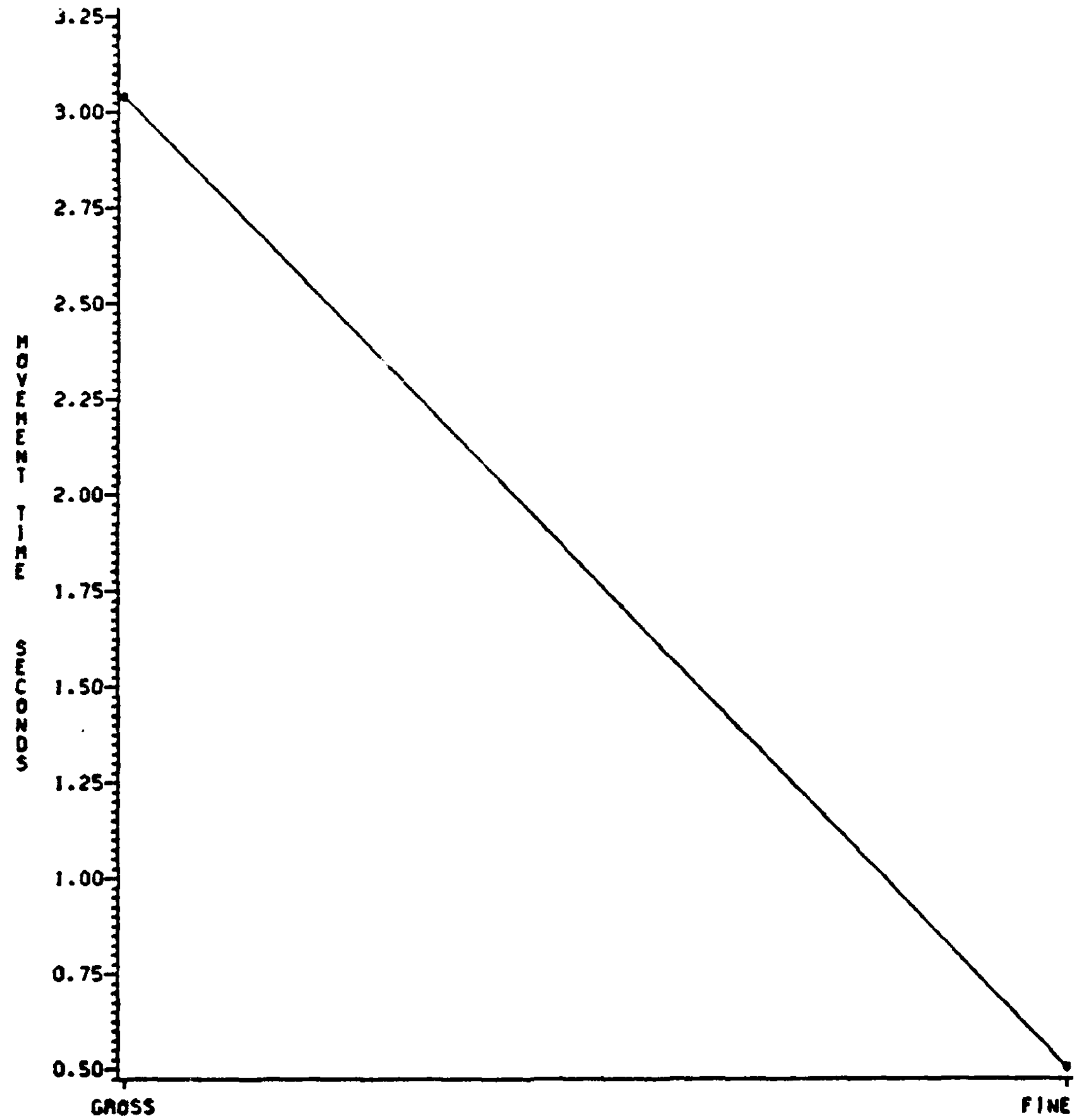


Figure 31: Movement type main effect for movement time.

The K1 × K2 interaction for movement time is significant. Movement time remains constant for the low and medium velocity gains across all position gains (Figure 32, Table 15). For zero velocity gain, movement time decreases as position gain increases from low to high. For high velocity gain, movement time increases as position gain increases from medium to high.

Movement time decreases as tablet size increases from small to medium for both low position gain and high position gain (Figure 33, Table 16). Movement time remains constant for medium position gain across all tablet sizes.

Movement time decreases for all target sizes as velocity gain increases from 0.0 to 0.1 and remains constant for the medium and large targets as velocity gain increases from 0.1 to 0.2 (Figure 34, Table 17). The increase in velocity gain from 0.2 to 0.3 does not affect movement time for large targets, but this increase in velocity gain results in slower movement times for the small and medium targets.

Gross movement time decreases as position gain increases from low to medium and remains constant as position gain increases from medium to high (Figure 35, Table 18). Fine movement time is constant as position gain increases from low to medium. Fine movement time increases as position gain increases from medium to high.

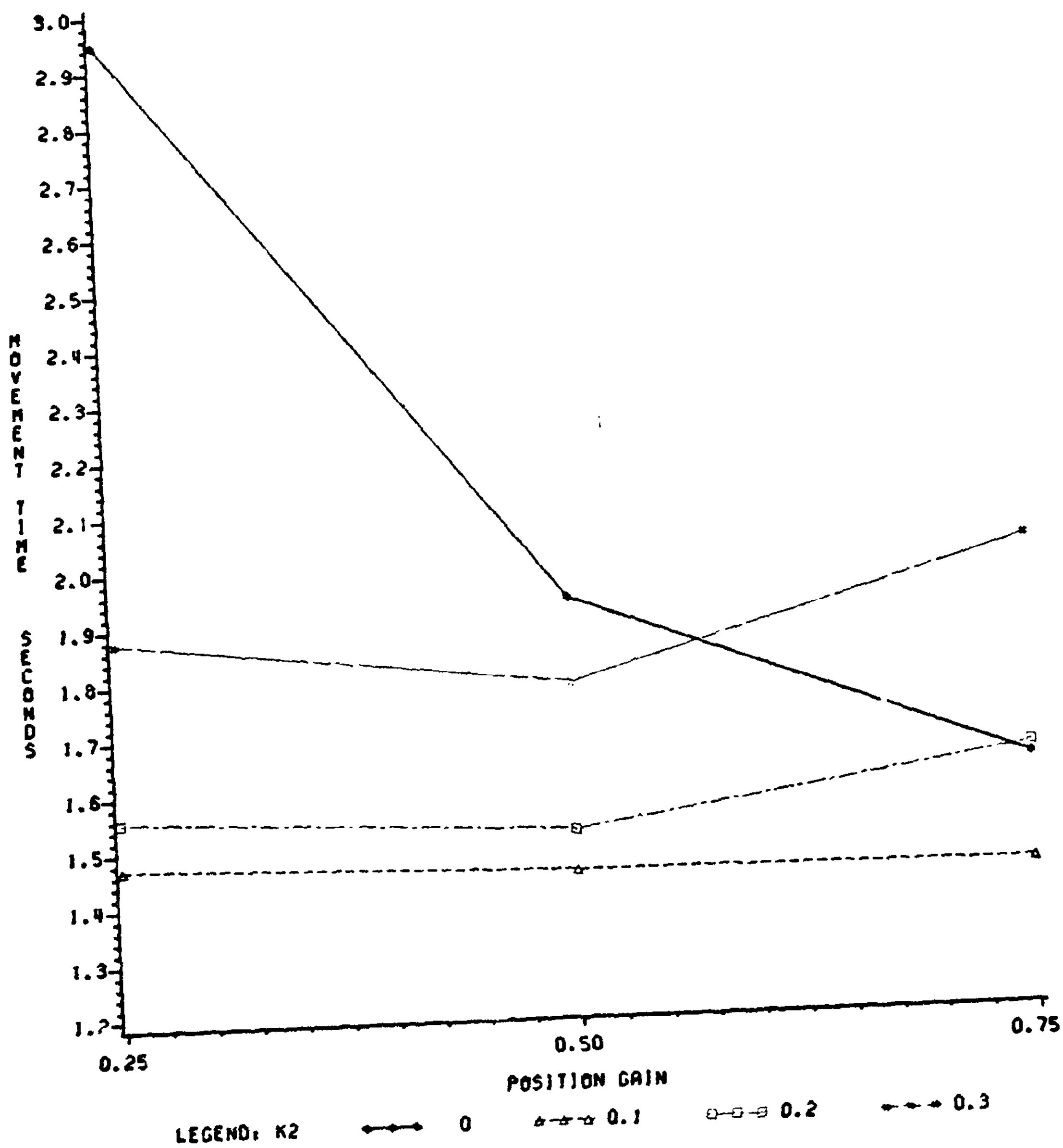


Figure 32: K1 x K2 interaction for movement time.

TABLE 15

Newman-Keuls Test Results for K1 x K2 Interaction for Movement Time

K1	K2	Mean Time					
0.75	0.1	1.44	A				
0.5	0.1	1.45	A				
0.25	0.1	1.47	A	B			
0.5	0.2	1.52	A	B			
0.25	0.2	1.56	A	B			
0.75	0.0	1.63		B			
0.75	0.2	1.65		B			
0.5	0.3	1.78			C		
0.25	0.3	1.88			C	D	
0.5	0.0	1.94			C	D	
0.75	0.3	2.02				D	
0.25	0.0	2.95					E

Alpha level = 0.05.

Means with the same letter are not significantly different.

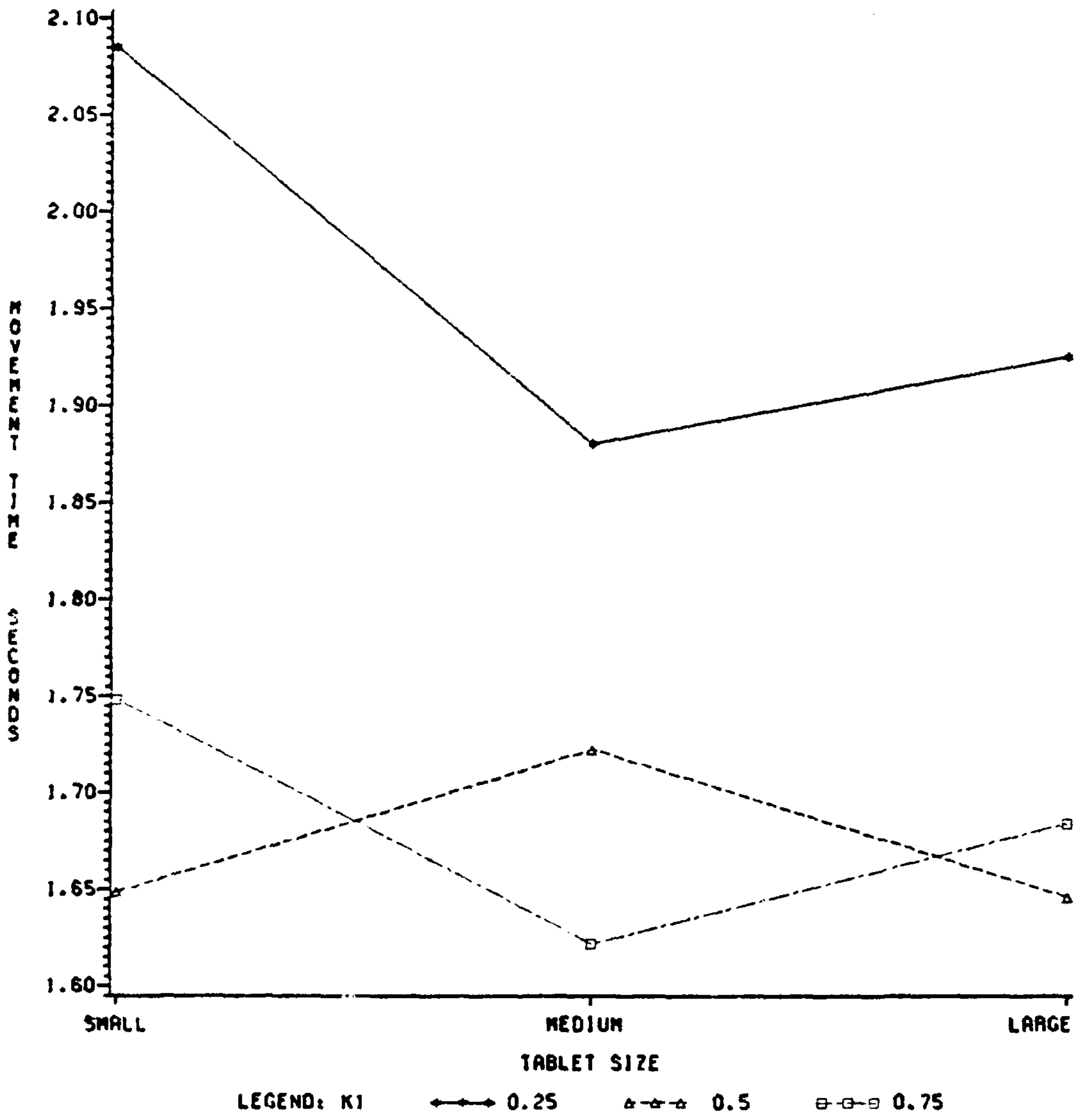


Figure 33: K1 x TS interaction for movement time.

TABLE 16

Newman-Keuls Test Results for K1 x TS Interaction for Movement Time

K1	TS	Mean Time	
0.75	med.	1.62	A
0.5	large	1.64	A B
0.5	small	1.65	A B
0.75	large	1.68	A B
0.5	med.	1.72	A B
0.75	small	1.75	B
0.25	med.	1.88	C
0.25	large	1.92	C
0.25	small	2.09	D

Alpha level = 0.05.

Means with the same letter are not significantly different.

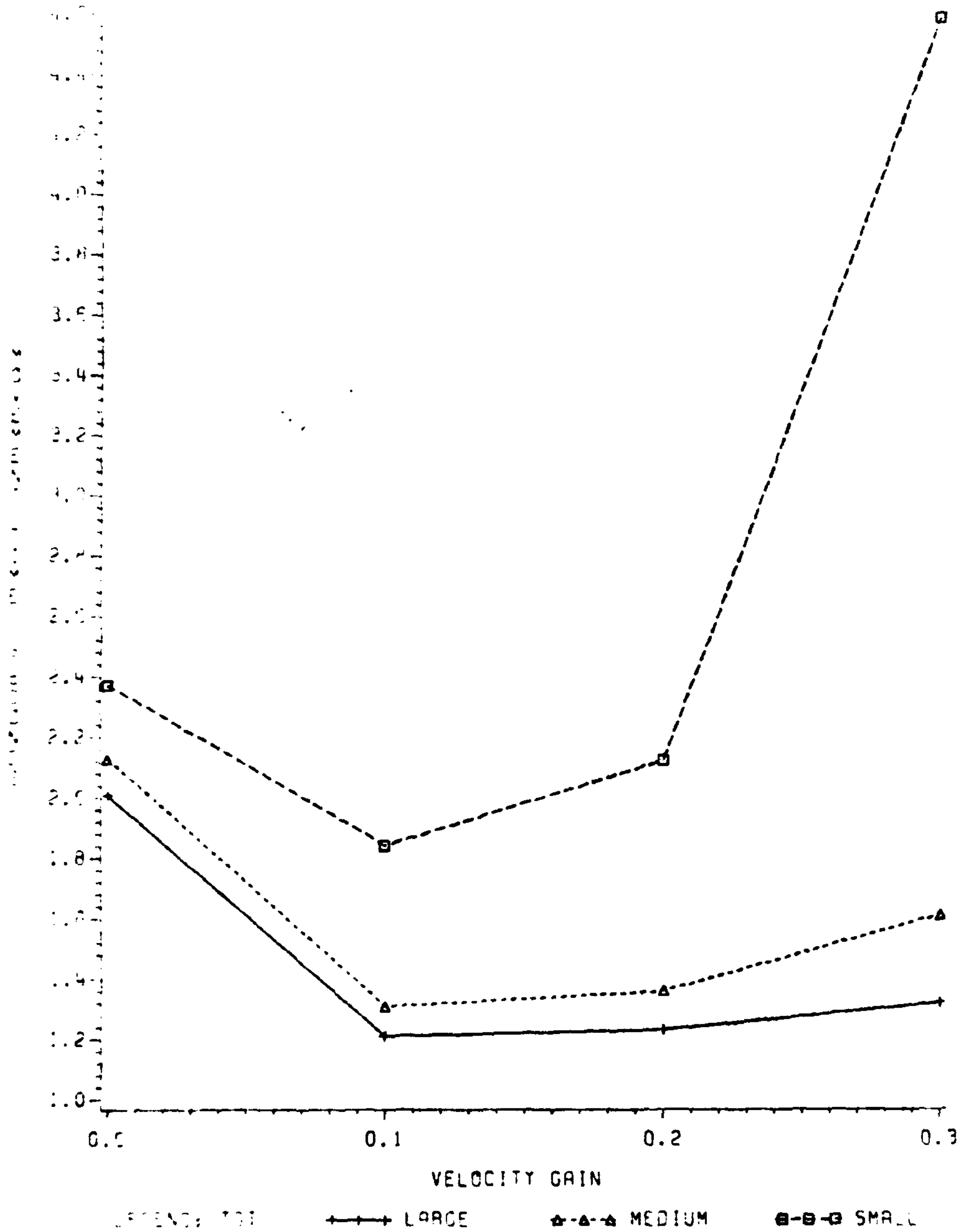


Figure 34: K2 x TGT interaction for movement time.

TABLE 17

Newman-Keuls Test Results for K2 x TGT Interaction for Movement Time

K2	TGT	Mean Time	
0.1	large	1.21	A
0.2	large	1.23	A
0.1	med.	1.31	A B
0.3	large	1.32	A B
0.2	med.	1.36	B
0.3	med.	1.61	C
0.1	small	1.84	D
0.0	large	2.01	E
0.2	small	2.12	F
0.0	med.	2.13	F
0.0	small	2.37	G
0.3	small	4.57	H

Alpha level = 0.05.

Means with the same letter are not significantly different.

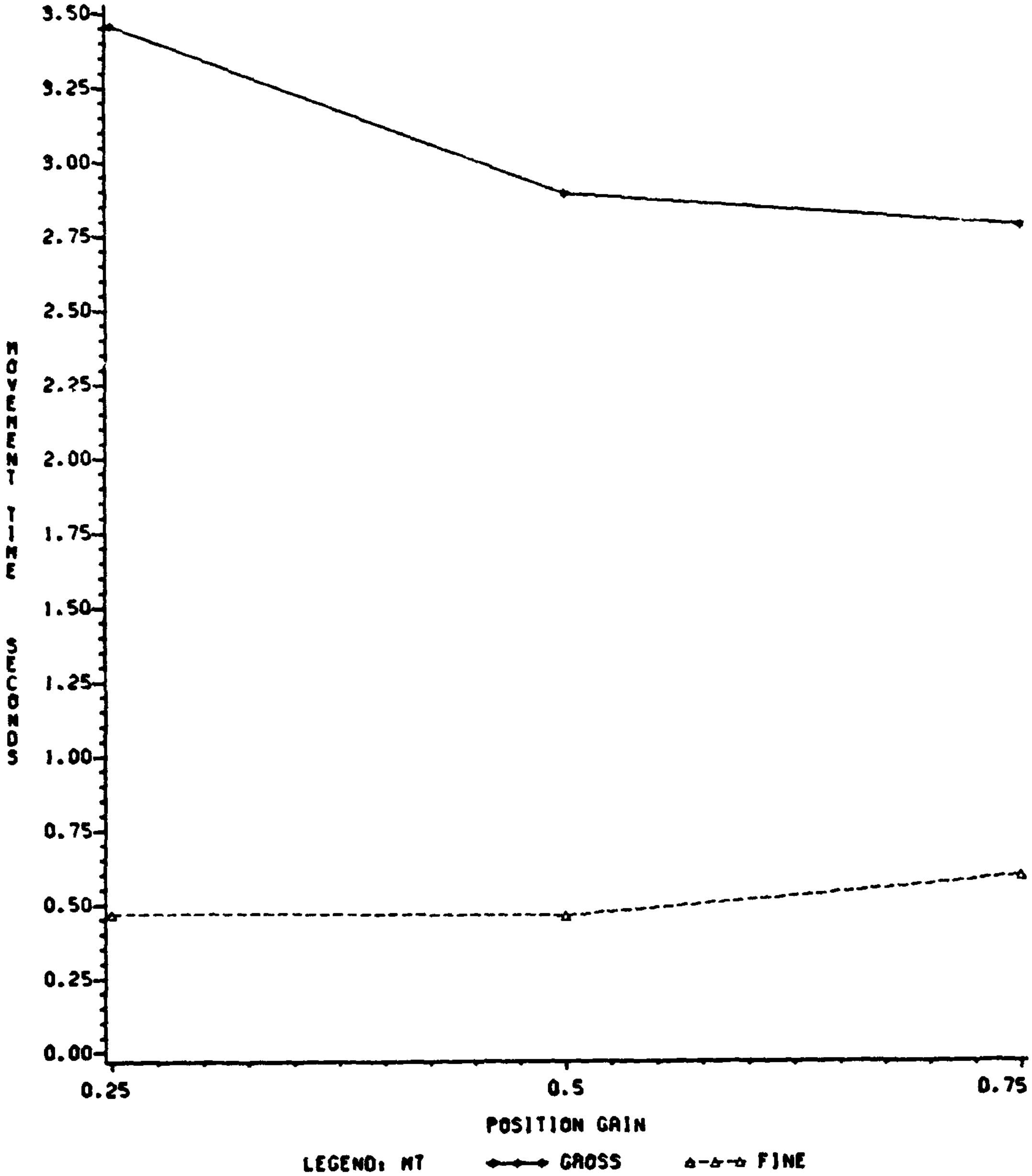


Figure 35: K1 x MT interaction for movement time.

TABLE 18

Newman-Keuls Test Results for K1 x MT Interaction for Movement Time

MT	K1	Mean Time	
fine	0.25	0.46	A
	0.50	0.47	A
	0.75	0.59	B
gross	0.75	2.78	C
	0.50	2.89	C
	0.25	3.46	D

Alpha level = 0.05.

Means with the same letter are not significantly different.

Gross movement time is significantly faster with non-zero velocity gains relative to zero velocity gain (Figure 36, Table 19). Fine positioning time increases as velocity gain increases.

Both gross movement and fine movement time decrease as target size increases (Figure 37, Table 20).

The K1 x K2 x TGT interaction is significant (Figure 38). A simple-effects F test (Table 21) shows that the effect of position gain is significant for K2 = 0.0, 0.2, and 0.3. At zero velocity gain, movement time decreases as position gain increases for all target sizes. At K2 = 0.1, movement time is constant across position gain for all target sizes. At K2 = 0.2 and K2 = 0.3, movement time increases for the small target size as position gain increases from medium to high. Movement time for the medium and large targets is constant across position gain at K2 = 0.2 and K2 = 0.3.

The effect of target size is significant for all levels of velocity gain. In each instance, movement time is slowest with the small targets and movement time is fastest with large targets.

The K1 x TGT interaction was significant for the velocity gains of 0.0 and 0.3. At the velocity gain of 0.3, movement time for medium and large targets remains constant as position gain increases from low to high. For small targets

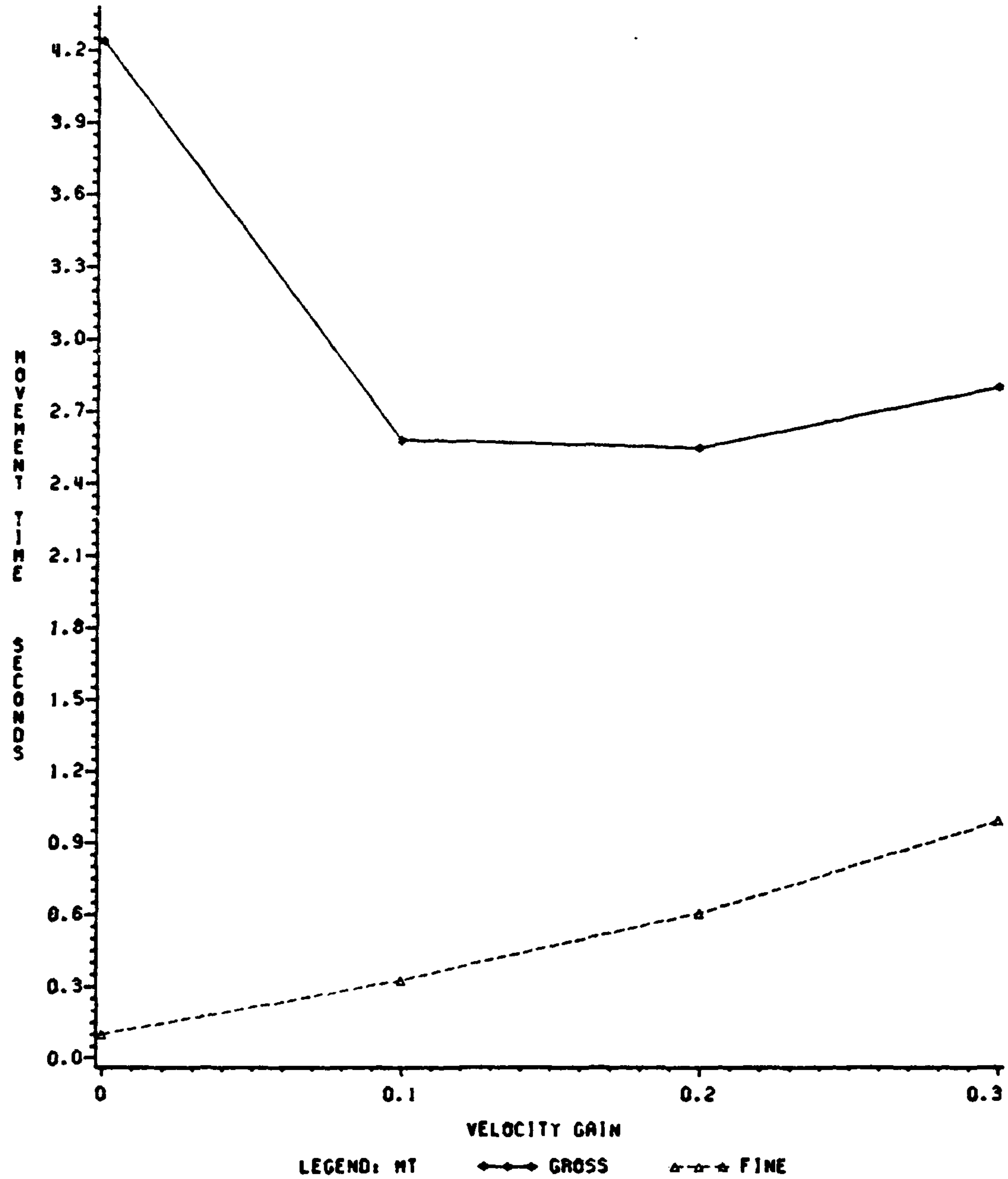


Figure 36: K2 x MT interaction for movement time.

TABLE 19

Newman-Keuls Test Results for K2 x MT Interaction for Movement Time

MT	K2	Mean Time	
fine	0.0	0.10	A
	0.1	0.33	B
	0.2	0.61	C
	0.3	0.99	D
gross	0.2	2.55	E
	0.1	2.58	E
	0.3	2.80	F
	0.0	4.23	G

Alpha level = 0.05.

Means with the same letter are not significantly different.

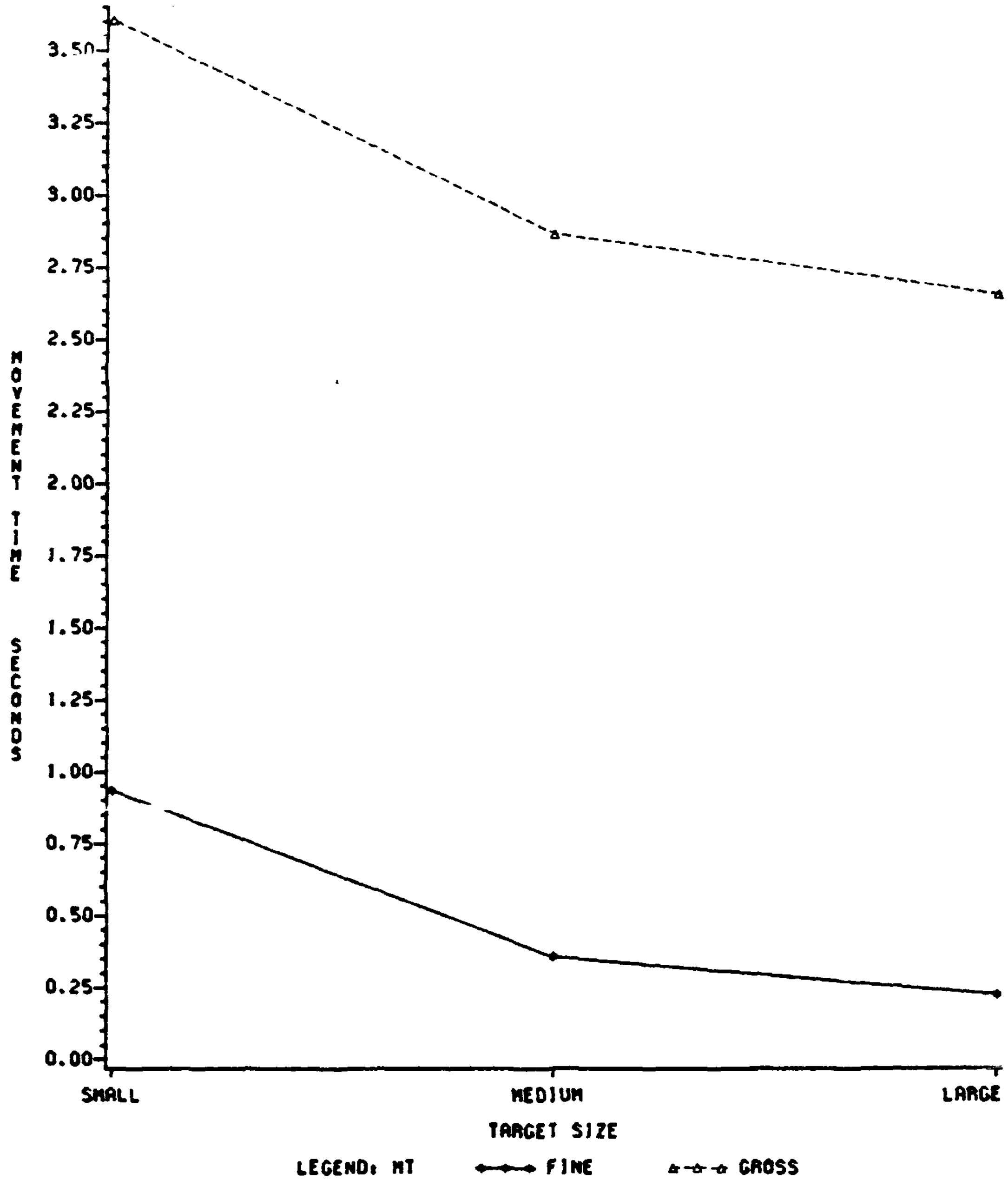


Figure 37: TGT x MT interaction for movement time.

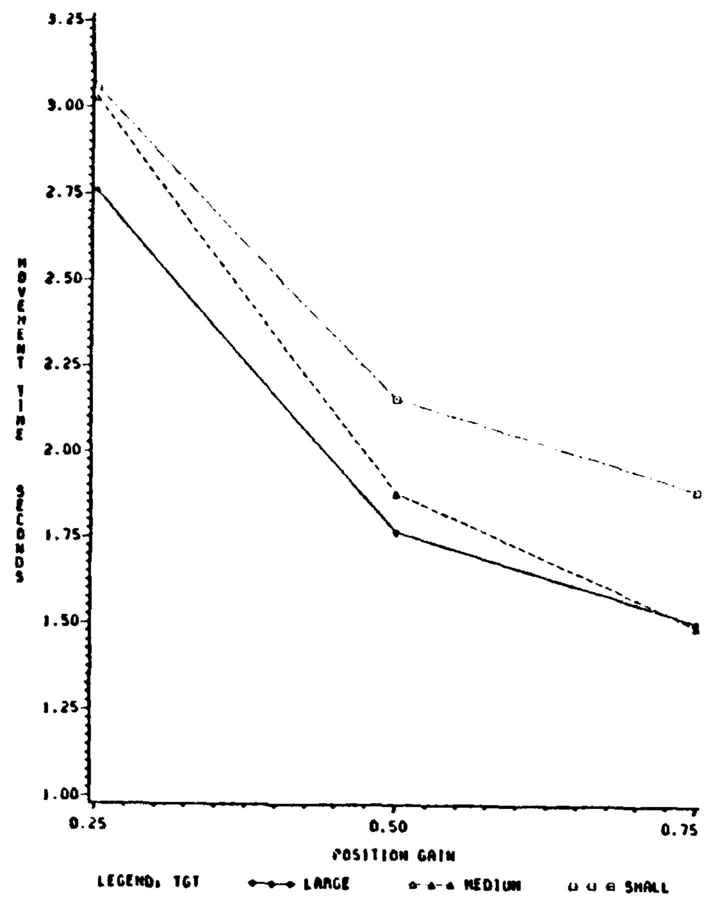
TABLE 20

Newman-Keuls Test Results for TGT x MT Interaction for Movement Time

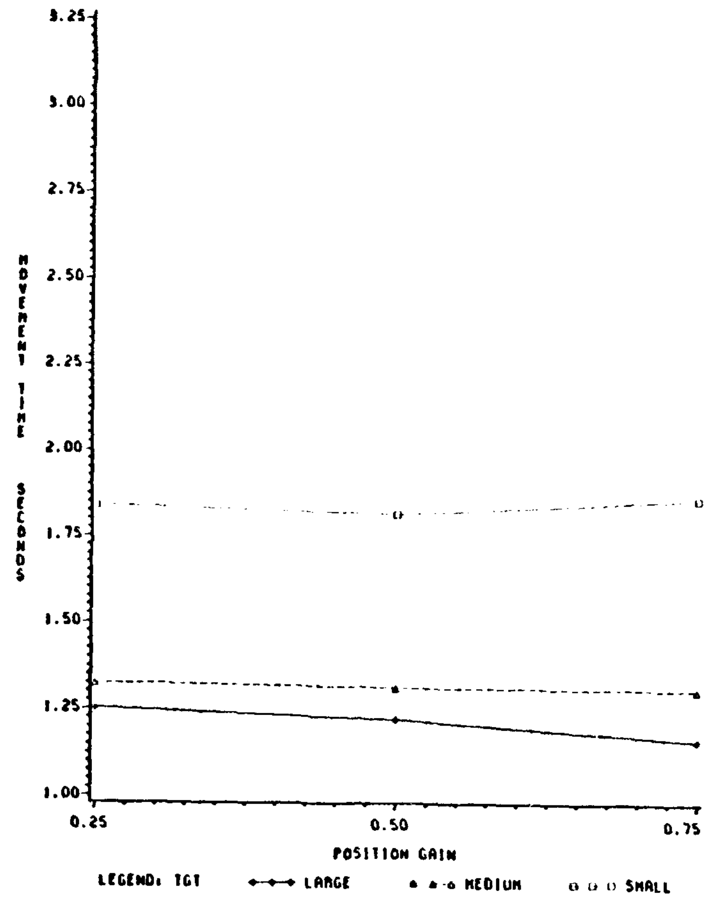
MT	TGT	Mean Time						
fine	large	0.23	A					
	med.	0.36		B				
	small	0.93			C			
gross	large	2.66				D		
	med.	2.86					E	
	small	3.61						F

Alpha level = 0.05.

Means with the same letter are not significantly different.

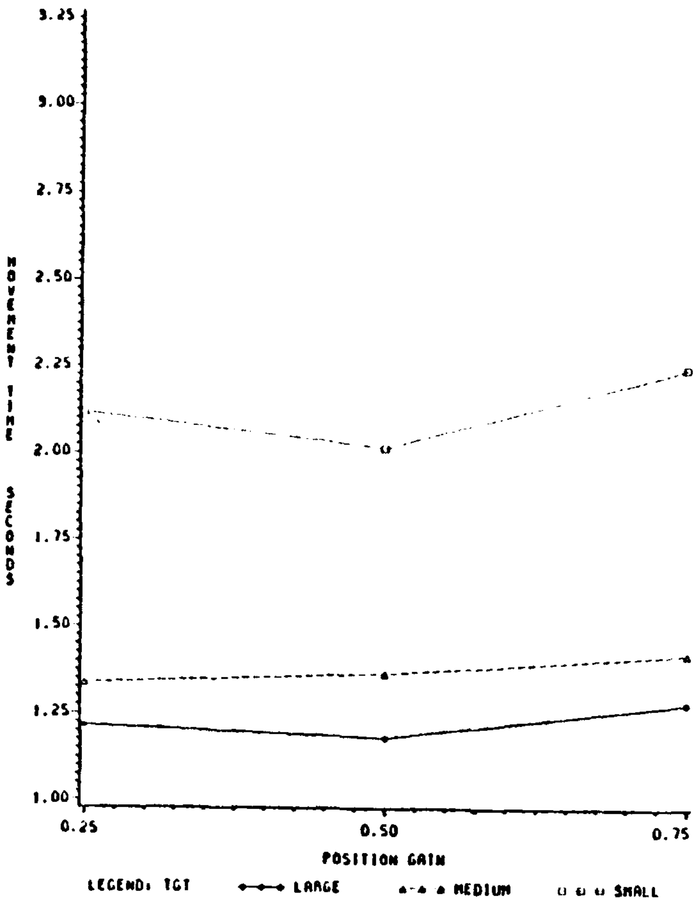


a. K1 x TGT interaction at K2 = 0.0

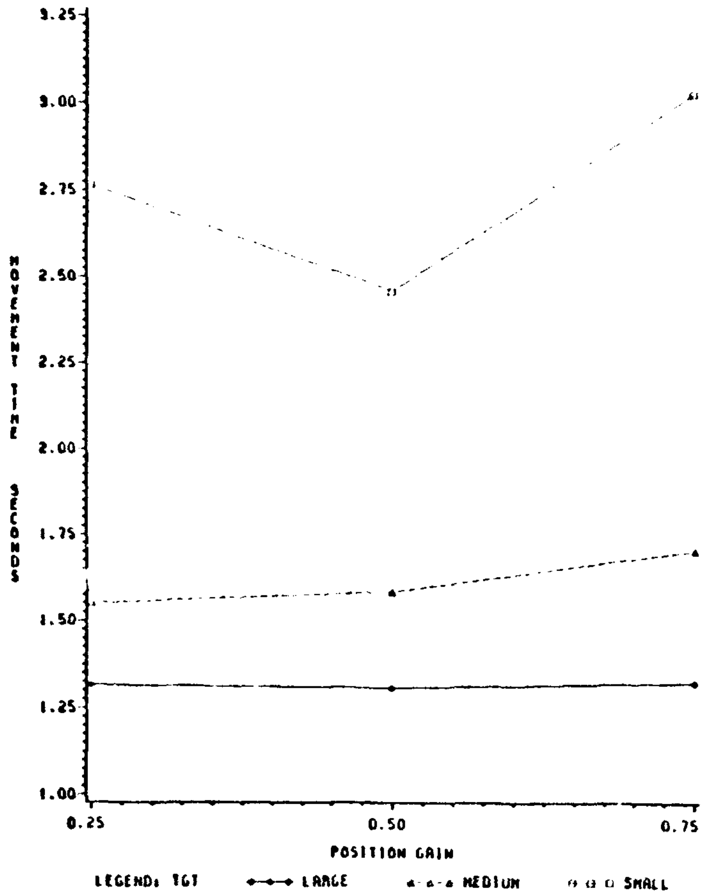


b. K1 x TGT interaction at K2 = 0.1

Figure 38: K1 x K2 x TGT interaction for movement time.



c. K1 x TGT interaction at K2 = 0.2



d. K1 x TGT interaction at K2 = 0.3

Figure 38: K1 x K2 x TGT interaction for movement time.

TABLE 21

Summary Table of the Individual Simple-Effects F-tests for Each Velocity Gain

Source	df	MS	F	
K2 = 0.0				
K1	2	103.02	429.25	*
TGT	2	7.02	29.25	*
K1 x TGT	4	0.69	2.88	*
K2 = 0.1				
K1	2	0.05	0.22	
TGT	2	24.33	101.35	*
K1 x TGT	4	0.07	0.30	
K2 = 0.2				
K1	2	0.94	3.89	*
TGT	2	50.28	209.48	*
K1 x TGT	4	0.16	0.66	
K2 = 0.3				
K1	2	3.03	12.63	*
TGT	2	123.91	516.30	*
K1 x TGT	4	1.65	6.88	*

* $p < 0.05$

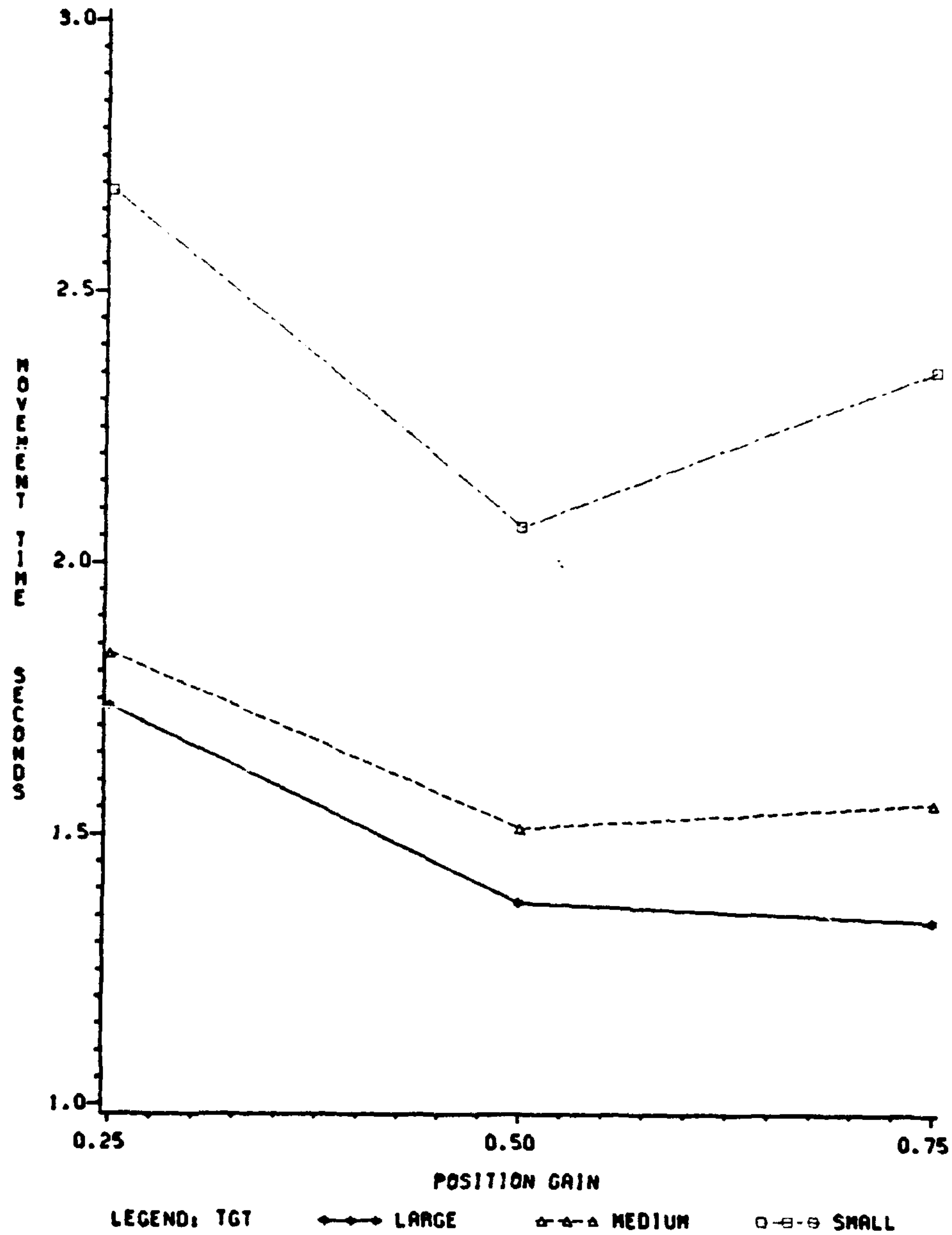
at velocity gain of 0.3, movement time increases as position gain increases from medium to high.

The K1 x TS x TGT interaction is significant (Figure 39). A simple-effects F test (Table 22) shows that the effect of position gain is significant for each tablet size. Low position gain results in the slowest movement time for all tablet sizes. Medium and high position gain had similiar movement times for all tablet sizes.

The effect of target size is also significant for each tablet size. For the small tablet size, movement time is not significantly different for medium and large targets. Movement time for small targets is significantly slower. For the medium and large tablet sizes, movement time increases as target size decreases.

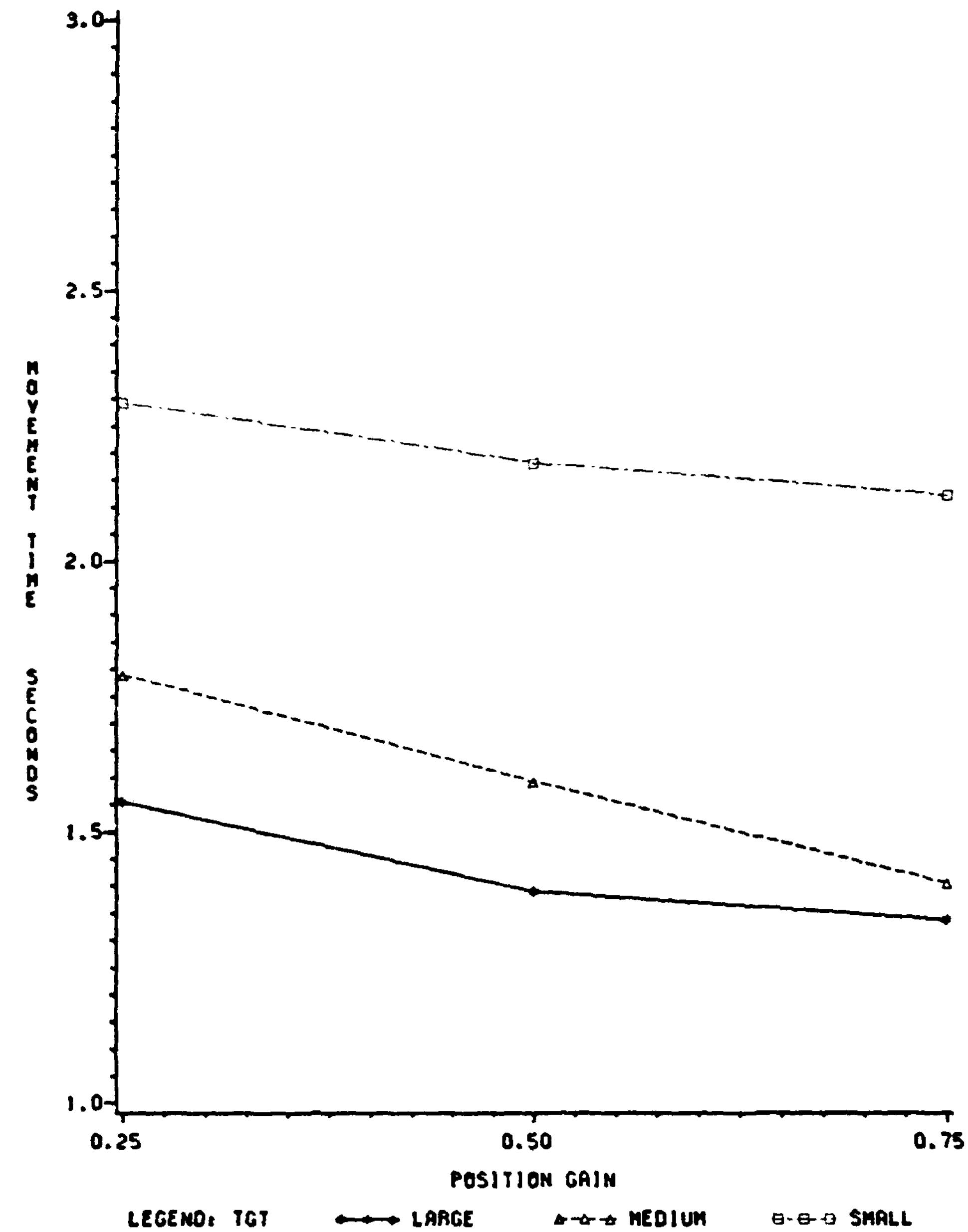
The K1 x TGT interaction is significant for the small and large tablet sizes (Table 23 and Table 24, respectively). For both the small and large tablet sizes, increasing position gain from medium to high increases movement time for small targets only.

The K1 x K2 x MT interaction is significant (Figure 40). A simple-effects F test (Table 25) shows that the effect of position gain is significant for both gross movement time and fine positioning time. The low position gain results in significantly slower gross movement time than the medium or



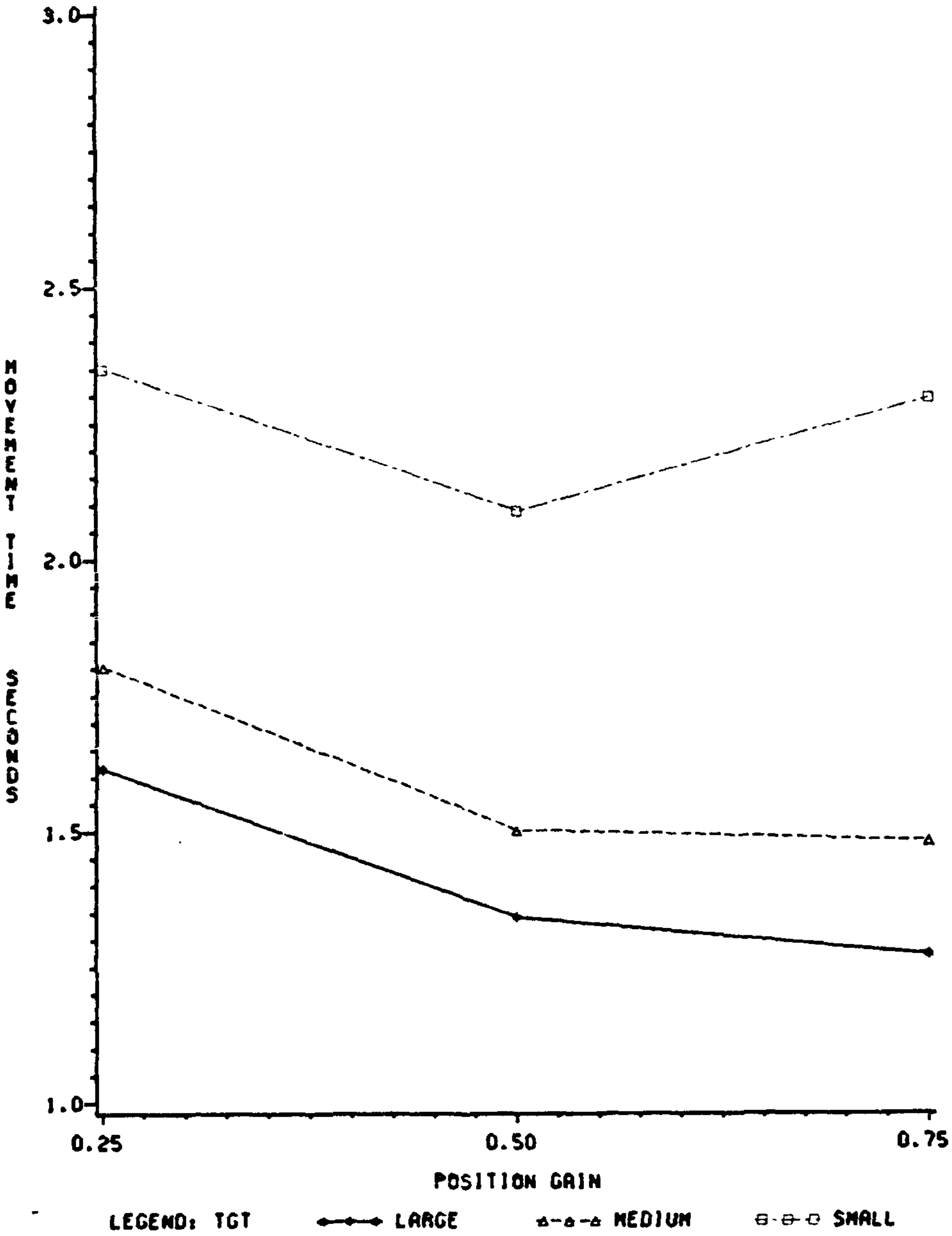
a. K1 x TGT interaction for small tablet size.

Figure 39: K1 x TS X TGT interaction for movement time.



b. K1 x TGT interaction for medium tablet size.

Figure 39: K1 x TS X TGT interaction for movement time.



c. K1 x TGT interaction for large tablet size.

Figure 39: K1 x TS X TGT interaction for movement time.

TABLE 22

Summary Table of the Individual Simple-Effects F-tests for Each Tablet Size

Source	df	MS	F
Small Tablet Size			
K1	2	26.53	119.85 *
TGT	2	52.16	235.63 *
K1 x TGT	4	3.02	13.64 *
Medium Tablet Size			
K1	2	4.87	22.02 *
TGT	2	47.17	213.09 *
K1 x TGT	4	0.33	1.47
Large Tablet Size			
K1	2	6.59	29.75 *
TGT	2	55.14	249.11 *
K1 x TGT	4	0.76	3.43 *

* $p < 0.05$

TABLE 23

Newman-Keuls Test Results of K1 x TGT Interaction for Small Tablet Size for Movement Time

K1	TGT	Mean Time	
0.75	large	1.34	A
0.50	large	1.37	A
0.50	med.	1.51	B
0.75	med.	1.56	B
0.25	large	1.74	C
0.25	med.	1.83	C
0.50	small	2.06	D
0.75	small	2.35	E
0.25	small	2.69	F

Alpha level = 0.05.

Means with the same letter are not significantly different.

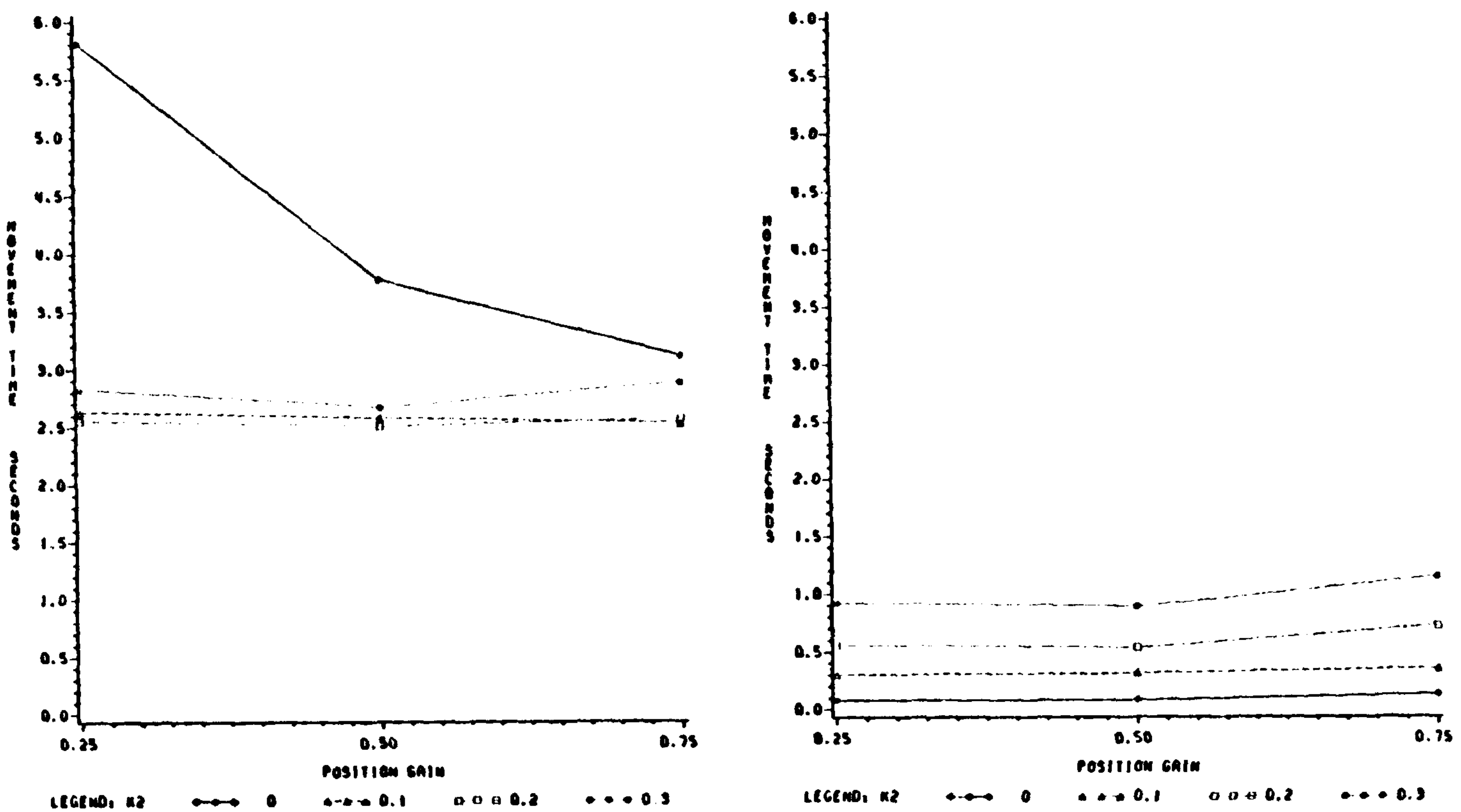
TABLE 24

Newman-Keuls Test Results of K1 x TGT Interaction for Large Tablet Size for Movement Time

K1	TGT	Mean Time	
0.75	large	1.27	A
0.50	large	1.34	A
0.75	med.	1.48	B
0.50	med.	1.50	B
0.25	large	1.62	B
0.25	med.	1.8	C
0.50	small	2.09	D
0.75	small	2.29	E
0.25	small	3.35	E

Alpha level = 0.05.

Means with the same letter are not significantly different.



a. K1 x K2 interaction for gross movement

b. K1 x K2 interaction for fine positioning

Figure 40: K1 x K2 x MT interaction for movement time.

TABLE 25

Summary Table of the Individual Simple-Effects F-tests for Each Movement Type

Source	df	MS	F
Gross Movement			
K1	2	57.54	213.11 *
K2	3	211.17	782.11 *
K1 x K2	6	52.04	192.74 *
Fine Positioning			
K1	2	2.34	8.66 *
K2	3	47.42	175.60 *
K1 x K2	6	0.35	1.29

* $p < 0.05$

high position gains. Fine positioning times for low and medium position gains are not significantly different, but are significantly shorter than for the high position gain.

The effect of velocity gain is significant for both gross movement and fine positioning. Gross movement time is significantly shorter with velocity gains of 0.1 and 0.2 than with velocity gains of 0.0 and 0.3. Fine positioning time increases as velocity gain increases. All velocity gains are significantly different for fine positioning time. Although fine positioning time increases with low and medium velocity gains, movement time decreases due to the impact of velocity gain on gross movement time (see Figure 29).

The K1 x K2 interaction is significant for gross movement time. Gross movement time remains constant for the 0.1 and 0.2 velocity gains across all position gains (Table 26). For zero velocity gain, gross movement time decreases as position gain increases from low to high. For high velocity gain, gross movement time increases as position gain increases from medium to high.

The K2 x TGT x MT interaction is significant (Figure 41). A simple-effects F test (Table 27) shows that the effect of velocity gain is significant for both gross movement time and fine positioning time. Velocity gains of 0.1 and 0.2 yield the shortest gross movement time. Fine positioning time increases as velocity gain increases.

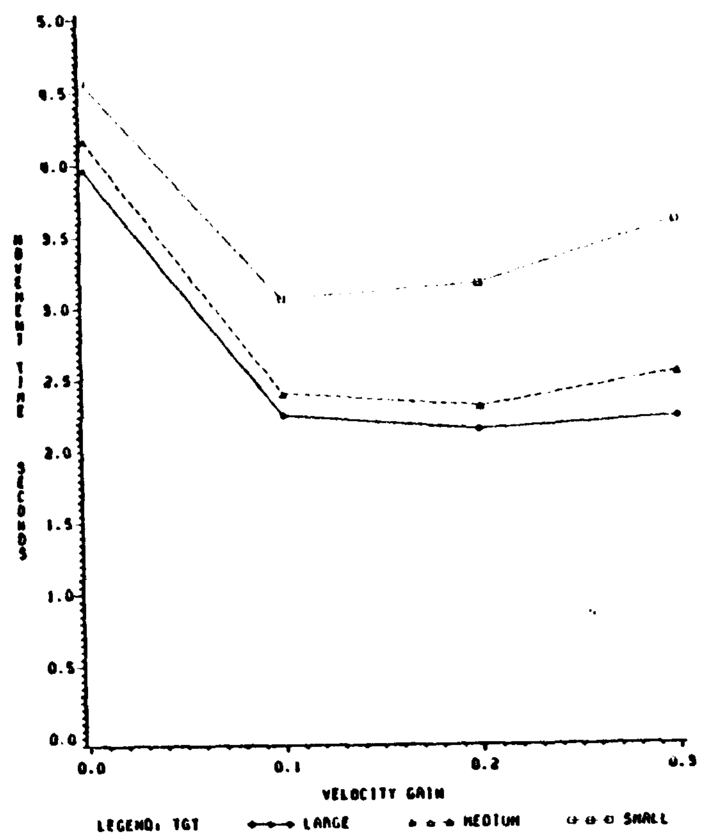
TABLE 26

Newman-Keuls Test Results of K1 x K2 Interaction for Gross Movement Time

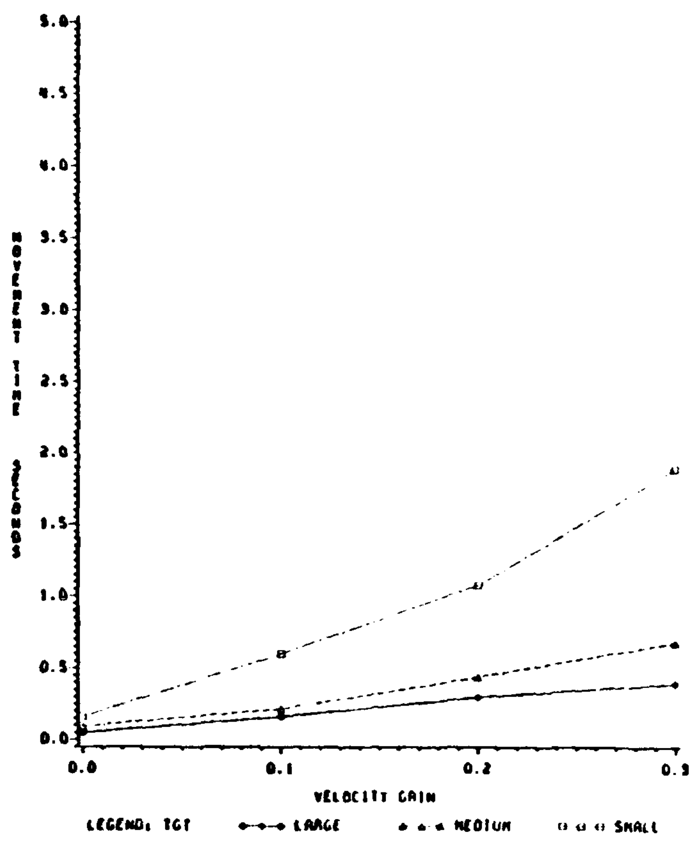
K2	K1	Mean Time						
0.2	0.50	2.51	A					
	0.25	2.55	A					
	0.75	2.57	A					
0.1	0.75	2.53	A					
	0.50	2.58	A					
	0.25	2.63	A	B				
0.3	0.50	2.67	A	B				
	0.25	2.83		B	C			
	0.75	2.89			C			
0.0	0.75	3.12				D		
	0.50	3.78					E	
	0.25	5.81						F

Alpha level = 0.05.

Means with the same letter are not significantly different.



a. K2 x TGT interaction for gross movement



b. K2 x TGT interaction for fine positioning

Figure 41: K2 x TGT x MT interaction for movement time.

TABLE 27

Summary Table of the Individual Simple-Effects F-tests for Each Movement Type

Source	df	MS	F
Gross Movement			
K2	3	211.17	1123.06 *
TGT	2	108.07	574.75 *
K2 x TGT	6	3.50	18.61 *
Fine Positioning			
K2	3	47.42	252.19 *
TGT	2	61.26	325.80 *
K2 x TGT	6	10.80	57.44 *

* $p < 0.05$

The effect of target size is significant for gross movement and fine positioning. For both gross movement and fine positioning, movement time increases as target size decreases. All target resolutions are significantly different for both gross movement and fine positioning.

The interaction of velocity gain with target size is significant for both gross movement and fine positioning. Gross movement time decreases for all target sizes as velocity gain increases from 0.0 to 0.1 and remains constant for all target sizes as velocity gain increases from 0.1 to 0.2 (Table 28). The increase in velocity gain from 0.2 to 0.3 does not affect gross movement time for large targets, but increases gross movement times for small and medium targets. As velocity gain increases, fine positioning time increases at a greater rate for small targets than for medium and large targets (Table 29).

The K1 x K2 x TGT x TS x MT interaction is statistically significant. However, the complexity of this interaction leads to no straightforward interpretation and it is therefore not discussed here.

TABLE 28

Newman-Keuls Test Results of K2 x TGT Interaction for Gross Movement Time

K2	TGT	Mean Time	
0.2	large	2.15	A
0.3	large	2.23	A
0.1	large	2.26	A
0.2	med.	2.31	A
0.1	med.	2.41	A B
0.3	med.	2.55	B
0.1	small	3.07	C
0.2	small	3.17	C
0.3	small	3.61	D
0.0	large	3.98	E
0.0	med.	4.17	F
0.0	small	4.57	G

Alpha level = 0.05.

Means with the same letter are not significantly different.

TABLE 29

Newman-Keuls Test Results of K2 x TGT Interaction for Fine Positioning Time

K2	TGT	Mean Time						
0.0	large	0.05	A					
0.0	med.	0.09	A					
0.1	large	0.16	A	B				
0.0	small	0.16	A	B				
0.1	med.	0.22	A	B				
0.2	large	0.30	A	B				
0.3	large	0.40		B	C			
0.2	med.	0.44		B	C			
0.1	small	0.60			C	D		
0.3	med.	0.68				D		
0.2	small	1.08					E	
0.3	small	1.89						F

Alpha level = 0.05.

Means with the same letter are not significantly different.

Subjective Data

A questionnaire was administered to the subjects after each condition to obtain their opinions on how physically or mentally fatiguing each condition was (Appendix D). A Friedman two-way analysis of variance was conducted because the questionnaire data did not appear to have interval properties. This analysis indicates that none of the conditions was significantly different from any other condition in terms of perceived physical or mental fatigue ($p > 0.20$).

Written comments were solicited upon completion of each position gain/velocity gain combination; these comments are summarized by the following statements. Zero velocity gain combined with low and medium position gain was generally considered too slow and very frustrating. The high position gain/zero velocity gain was also considered slow but not as frustrating. A velocity gain of 0.1 combined with any position gain was considered by most subjects to be easy with no fine positioning difficulties. A few subjects felt that the high position gain was too "fast" with any non-zero velocity gain, hindering control of the cursor. The comments on a velocity gain of 0.2 combined with low or medium position gains were mixed. Some subjects felt these combinations were easy, while others felt that the cursor

was difficult to control. The velocity gain of 0.2/high position gain combination and all conditions with a velocity gain of 0.3 were considered difficult and much too "fast." However, in each of these conditions a minority of subjects felt that the task was easy and the cursor controllable.

At the conclusion of the study, subjects were asked which tablet size they preferred. Six subjects preferred the medium tablet, four preferred the large tablet, one preferred the small tablet, and one subject had no preference. Subjects who preferred the medium tablet thought that the large tablet had too much extra space and that energy was wasted by attempting to use all the tablet area. Some subjects preferred the large tablet with low position gains because a single stroke on the large tablet resulted in more movement (because of the increased tablet area) than a single stroke on a small or medium tablet.

Training Effects

The data were analyzed to see if performance improved over time (i.e., increased target acquisition rate, fewer entries into the target prior to confirmation, and greater accuracy) (Table 30). Target acquisition rate increased significantly over time. The greatest improvement was from day 1 to day 2 with an average of 1.4 more targets per

TABLE 30

Performance Measures across Days

	Day 1	Day 2	Day 3
Rate (targets/min.)	14.03	15.41	16.19
Entries into target	1.42	1.38	1.31
Error	1.02	1.01	1.02

minute acquired on day 2 than on day 1 (p = 0.0154). The rate also significantly increased from day 2 to day 3 (p = 0.0023). In terms of number of target entries prior to confirmation, significantly fewer entries were made on day 3 than on day 2 (p = 0.0171). There was no significant difference between the number of target entries on day 1 and day 2. There was no significant difference in terms of percentage error over days. The order of tablet size presentation was counterbalanced across days to protect against learning effects biasing the results.

DISCUSSION

D/C Gain

The results indicate that a lead-lag compensation system achieves higher target acquisition rates than a pure position gain system. The addition of a velocity gain component to a pure position gain system achieves target acquisition rates greater than or equal to the original position gain system in every case but that in which a high velocity gain is combined with a high position gain (Figure 15). All of the position gain/velocity gain combinations which achieve the highest target acquisition rates incorporated a non-zero velocity gain component. These combinations recommended for use are low, medium, or high position gain (K1 = 0.25, 0.50, 0.75) coupled with velocity gain of 0.1; and low or medium position gain coupled with velocity gain of 0.2.

The addition of a velocity gain component to a pure position gain system substantially reduces gross movement time (Figure 40a). The shortest gross movement times are achieved with velocity gains of 0.1 and 0.2. These short movement times are achieved at all levels of position gain

(K1 = 0.25, 0.50, 0.75). Fine positioning time increases with increasing velocity gain (Figure 36). The addition of a velocity gain component of C.1 or 0.2 to a pure position gain system, however, achieves gross movement time reductions that more than counterbalance this increase in fine positioning time.

The addition of a velocity gain component to a pure position gain system causes error rates to increase from approximately one percent of the responses to about two percent (Figure 25). The increase in overall acquisition rate gained with lead-lag compensation would more than compensate for the accompanying increase in error rate in most applications.

Tablet Size

No specific tablet size can be recommended based on this research. Smaller tablet sizes appear to achieve performance levels comparable to those obtained with the largest tablet size. Thus, if the work area is limited in size, it appears that a small tablet may be used without significant human performance decrements.

The significant position gain x tablet size interaction for target acquisition rate (Figure 16) indicates that with medium to high position gain (K1 = 0.5, 0.75), all tablet

sizes achieve reasonably high target acquisition rates. Low position gain (K1 = 0.25) achieves a particularly low target acquisition rate with a small tablet. This is most likely because several strokes across the tablet are required with this combination to move the cursor across the screen. It is recommended that such a combination not be used.

An inspection of the position pain x tablet size interaction and the position gain x tablet size x target size interaction (Figures 16 and 20, respectively) suggests that a high position gain is preferable to a medium position gain for use with a medium tablet size, enhancing the acquisition rate for all target sizes. For the large tablet size, however, high position gain appears to degrade the acquisition rate of small targets. Averaged across all target sizes, medium position gain and high position gain achieve essentially identical acquisition rates for the large tablet size.

Target Size

The effect of target size is clear. Human performance deteriorates as target size decreases in terms of all the performance metrics considered (Figures 14, 23, 26, 30, and 37). This result is predictable and is consistent with those of previous studies (Arnaut and Greenstein, 1985;

Gomez et al., 1982; Whitfield et al., 1983). Acquisition of small targets (0.51 cm^2), relative to medium and large targets (2.04 cm^2, and 4.63 cm^2, respectively), is particularly difficult. Clearly, the use of small targets should be avoided when task requirements permit.

The position gain x target size interaction for target acquisition rate (Figure 17) indicates that increasing position gain differentially affects the acquisition of different target sizes. As position gain increases from medium to high (K1 = 0.5 to K1 = 0.75), the acquisition rate for large targets continues to increase. The acquisition rate for small and medium targets appears to begin leveling off, however. This suggests that beyond a certain point, increases in position gain degrade target acquisition performance and this degradation appears first with smaller targets.

The velocity gain x target size interaction is significant for target acquisition rate, movement time, and number of target entries prior to confirmation. These data consistently indicate that increasing velocity gain differentially affects the acquisition of different size targets. As velocity gain increases from 0.2 to 0.3, the gross movement time for large targets is unaffected (Figure 41a). The gross movement time for small and medium targets,

however, increases. The fine positioning time and number of target entries data (Figures 41b and 24, respectively) indicate that while increases in velocity gain increase the difficulty of fine positioning at all target sizes, the increase in difficulty is particularly rapid for small targets. Thus, as the target acquisition rate data suggest (Figure 18), the addition of a velocity gain component of 0.1 to a pure position gain system enhances performance for all target sizes but more so for medium and large targets. Increases of velocity gain from 0.1 to 0.3 degrade performance for all target sizes, but most for small targets.

CONCLUSIONS

A lead-lag controller is a viable alternative to a pure position gain system. All of the position gain/velocity gain combinations which achieve the highest target acquisition rate incorporated lead-lag compensation.

For the tablet sizes considered in this experiment, it has been shown that any tablet size may be used if the appropriate position gain/velocity gain combination is chosen. Tablet size is a consideration when low position gains are employed; in this case, larger tablets improve performance, and should therefore be employed.

Data tablets have become more available in recent years and are being used more often for a wide variety of tasks. Additional research should be conducted to investigate more thoroughly the design and use of data tablets. In this research, stylus operation of a lead-lag compensated system was considered. The results may not be extrapolated to finger operation of such a system. Thus, this is an additional factor which should be considered. Ellingstad et al. (1985) considered finger versus stylus operation in their research; they found that stylus operation was faster

and more accurate. However, they considered a single stylus type with a pure position gain system. Thus, finger versus stylus operation of a lead-lag compensated system might be investigated. Alternatively, a study should be conducted in which various stylus types are used and operator performance with each type is determined.

Finally, a major use of data tablets has been for graphics creation. A subtask of the graphics creation task may require moving the cursor from one point of the drawing to another point on the drawing. In circuit design tasks, these points are quite precise. This subtask of graphics creation is quite different from the task in this experiment. Thus, an initial study examining the use of a lead-lag controller for a graphics creation task should be performed. It is possible that the optimum coefficient values for a lead-lag controller for a graphics task may be very different from the coefficient values identified in this study.

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APPENDIX A

DERIVATION OF W_L AND K3

I. DERIVATION OF w_L, the 3 dB corner frequency for the onset of gain related to the velocity of the control input, in terms of K_1, K_2, and w_H.

Starting with the transfer function of Equation (1):

$$G(s) = K_1 + \frac{K_2 s}{(s/w_H) + 1}$$

$$= \frac{K_1[(s/w_H) + 1] + K_2 s}{(s/w_H) + 1}$$

$$= \frac{K_1(s/w_H) + K_1 + K_2 s}{(s/w_H) + 1}$$

$$= \frac{[K_2 + (K_1/w_H)]s + K_1}{(s/w_H) + 1}$$

$$= \frac{[(K_2 w_H + K_1)/w_H]s + K_1}{(s/w_H) + 1}$$

$$= \frac{K_1\left(\dfrac{K_2 w_H + K_1}{K_1 w_H}\right)s + K_1}{(s/w_H) + 1}$$

$$= K_1 \frac{\left[\dfrac{(K_2 w_H + K_1)s}{K_1 w_H} + 1\right]}{(s/w_H) + 1}$$

$$= \frac{K_1\left[s/\left(\dfrac{K_1 w_H}{K_2 w_H + K_1}\right) + 1\right]}{(s/w_H) + 1}$$

$$= \frac{K_1[(s/w_L) + 1]}{(s/w_H) + 1}$$

where w_L is the 3 dB corner frequency for the onset of gain related to the velocity of the control input. Therefore,

$$w_L = \frac{K_1 w_H}{K_2 w_H + K_1}$$

II. DERIVATION OF K_3, the maximum total gain applied to high velocity inputs in terms of K_1,K_2, and w_H.

Starting with the transfer function of equation (1):

$$G(s) = K_1 + \frac{K_2 s}{(s/w_H) + 1}$$

$$= \frac{K_1[(s/w_H) + 1] + K_2 s}{(s/w_H) + 1}$$

$$= \frac{K_1(s/w_H) + K_1 + K_2 s}{(s/w_H) + 1}$$

$$= \frac{(w_H/s)}{(w_H/s)} \; \frac{K_1(s/w_H) + K_1 + K_2 s}{(s/w_H) + 1}$$

$$= \frac{K_1 + K_1(w_H/s) + K_2 w_H}{1 + (w_H/s)}$$

But $K_3 = \lim_{s \to \infty} | G(s) | = K_1 + K_2 w_H.$

Appendix B

PARTICIPANT'S INFORMED CONSENT

As a participant in this experiment, you have certain rights. The purpose of this document is to obtain your consent to participate and to inform you of your rights as a participant.

This study investigates a computer input device, the digitizer or touch tablet. There is presently a lack of specifications available to guide designers in the development of these input devices. This information is needed so that these devices may be employed effectively. This research is being conducted in the Human Factors Laboratory of the Department of Industrial Engineering and Operations Research. The research team for this experiment consists of Ms. Jane A. Becker and Dr. Joel S. Greenstein.

Your task as a participant in this study is to use the digitizer tablet to acquire designated targets on the graphics monitor. Participation in the study is entirely voluntary. If you choose to participate you will receive instruction in the use of the digitizer tablet. Each experimental session will consist of twelve blocks of trials with brief rest breaks between blocks. The entire experiment will require about six hours to complete. You will receive $21.00 for completing the experiment.

We hope that this experiment will be an interesting experience for you. It is possible that at times you may feel frustrated or stressed. Your performance on the task reflects the difficulty of the task, not your personal abilities or talents.

Your rights are as follows:

1. You have the right to stop participating in the experiment at any time. If you choose to terminate the experiment, you will receive pay only for the proportion of time you participated.

2. You have the right to see your data and to withdraw them from the experiment. If you decide to withdraw your data, please notify the experimenter immediately. Otherwise, identification of your particular data will not be possible, because the data will be separated from your name.

3. You have the right to be informed of the overall results of the experiment. If you wish to receive a synopsis of the results, include your name and address (three months hence) with your signature below. If more detailed information is desired after receiving the synopsis, please contact the Human Factors Laboratory, and a full report will be made available to you.

Your participation is greatly appreciated. If you have any questions about the experiment or your rights as a participant, please do not hesitate to ask. We will do our best to answer them, subject only to the constraint that we do not want to pre-bias the experimental results.

Should you have any additional questions or problems, contact Dr. Joel S. Greenstein, Assistant Professor, at 961-6339, or Mr. Charles D. Waring, Chairman of the Institutional Review Board for Research Involving Human Subjects, at 961-5284.

Your signature below indicates you have read the above stated rights and you consent to participate. If you include your name and address below, a summary of the experimental results will be sent to you.

____

Signature

____

Printed Name

____

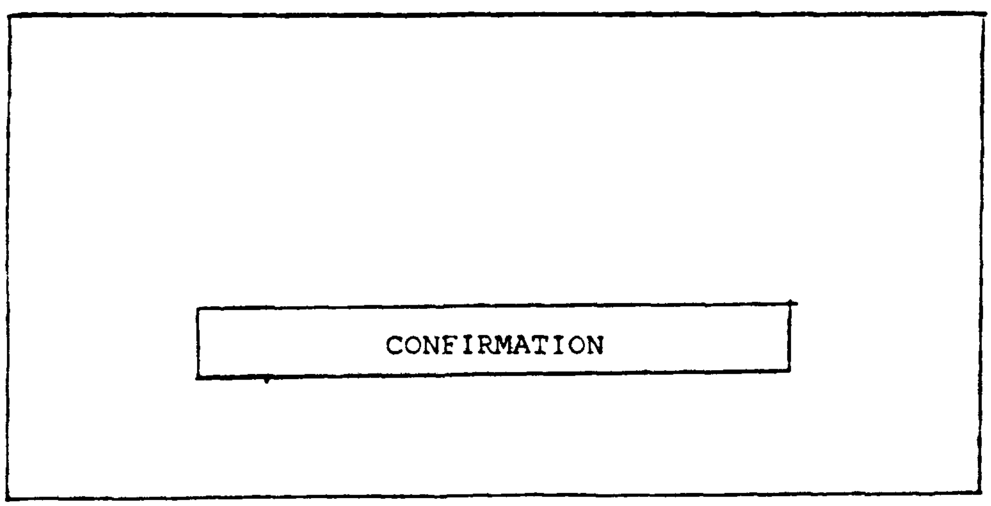
City, State, Zip

INSTRUCTIONS

A touch tablet is a computer input device which can be used for tasks such as word processing, computer aided design, and developing graphics. The information gained from this study will aid in developing human factors guidelines so that touch tablets may be more easily employed.

In this experiment you will be required to select a target presented on the display as quickly and as accurately as possible by moving the cursor into the target and then confirming your selection.

On the table in front of you is a touch tablet. At the bottom there is a large rectangle. This area is the confirmation area, as shown in the following diagram.



Press the confirmation area now, and an example of the display will appear. Do not press the touch tablet again until you are instructed to do so.

The cursor is the crosshair (+) which you see in the center of the display. A target can be one of the boxes in the menu that you now see on the left and right sides of the display, or it may be a box which will appear in the center area of the display.

At the beginning of each trial, a display like the one which is now on the screen will be presented. One of the targets will be highlighted (filled in with white). The highlighted target is the one you must select. To do so, you will place the stylus on the touch tablet and move the stylus until the cursor is inside the target.

When you place the stylus on the tablet the cursor will stay where it is on the display. Movement of the stylus across the tablet will move the cursor from this <u>current</u> position. Thus, note that every time you place the stylus on the tablet, the cursor remains where it is on the display.

You may place the stylus anywhere on the tablet to initiate cursor movement. If the stylus touches the edge of the tablet, simply lift up the stylus and place it down elsewhere on the tablet.

The center of the cursor must be inside the highlighted area for your selection to be correct. During the practice sessions, it is a good idea to try putting the cursor on the sides and corners of the targets and then confirming your selection. You will then have an idea as to when a selection will be considered correct. When moving the stylus on the touch tablet, be sure that your hands do not touch any other area of the tablet.

Once you are sure that the cursor is inside the target, lift the stylus and with your other hand press the confirmation area on the tablet. If your target selection was correct, a high frequency auditory tone will sound. If your selection was incorrect, a low frequency tone will be presented.

After a two-second pause, a new target will be presented and two brief tones will sound to indicate the beginning of the next trial. As soon as the two tones sound, the trial begins, and the clock will begin to time your response.

Each day you will use a different tablet size and will complete twelve sets of trials with that tablet size. In each set, the <u>control-display gain</u> will be changed. Control-display gain refers to the cursor movement produced on the screen in response to movements of the stylus on the touch tablet. In this study the control-display gain

consists of both position gain and velocity gain. Position gain refers to the amount of cursor movement on the screen in response to movements of the stylus on the touch tablet. Velocity gain refers to the speed of cursor movement on the screen in response to movements of the stylus on the touch tablet. Therefore the cursor will move farther when you move the stylus quickly then when you move the stylus slowly. During the practice sessions it is a good idea to vary how fast you move the stylus so that you can get a feel for the cursor movement. In one set, the cursor will move the same distance as the stylus moves on the tablet.

You will be given a chance to practice with the gain values before the actual timed set of trials begins. You will be required to select 30 targets in each of the twelve sets of trials. Try to select the targets as quickly as possible while minimizing errors. At the end of each set, a message will be displayed informing you that the trial block is finished. In addition, the number of correct target selections for that set of trials will be presented. At that point, inform the experimenter that the trial block is completed and you will be asked to complete a brief questionnaire. You will then receive a brief rest break before the next set begins.

When you are ready to begin, the experimenter will train you on the use of the touch tablet. You will spend appromately half an hour learning how to use the tablet and becoming familiar with the concept of velocity aiding.

Do you have any questions?

Appendix C

PRACTICE SESSION

The next half hour will be spent giving you practice on the use of the touch tablet. You will complete 15 trials in each of three set-ups.

The first set-up consists of a straight position gain system. Thus, the cursor moves the same distance that you move the stylus. Pick up the stylus and hold it vertically (! to the tablet). Move the stylus on the tablet back and forth and around in circles until you feel comfortable with the cursor movement. Now move the stylus quickly and slowly and observe the cursor movement.

OK. Complete the 15 trials. Move the cursor into the highlighted target, lift the stylus, and press the confirm area with your other hand.

The next set-up is of a position gain plus a low velocity gain system. Thus, the cursor movement depends upon the speed at which you move the stylus. The faster you move the stylus, the farther the cursor will travel. Practice with this system until you feel comfortable with the cursor movement.

Complete the 15 trials.

The third set-up is a position gain plus a high velocity gain system. Again cursor movement depends upon stylus speed. Practice with this system until you feel comfortable with the cursor movement.

Complete the 15 trials.

This completes the practice session.

Do you have any questions?

Appendix D

QUESTIONNAIRE 1

Subj ________
K1 ________
K2 ________
Size ________

How physically tiring was this gain value?

1	2	3	4	5
very tiring		somewhat tiring		not at all tiring

How mentally fatiguing was this gain value?

1	2	3	4	5
very fatiguing		somewhat fatiguing		not at all fatiguing

Please comment on this gain.

____

____

____

____

Appendix E

QUESTIONNAIRE 2

Subj ________

Which tablet size did you prefer? (Check one)

small ________

medium ________

large ________

no preference ________

Why? ____

____

____

____